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Effects of Automated Irrigation Systems and Water Regimes on Soil Properties, Water Productivity, Yield and Fruit Quality of Date Palm

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Abstract: Applications of modern micro-irrigation methods are inevitable for optimum water use due to the limitations imposed by irrigation water resource scarcity. Regardless of water shortages and associated challenges in dry areas, the irrigation of date palm trees consumes an excessive quantity of water annually using conventional irrigation methods. Therefore, the present study was designed to evaluate the effects of modern surface and subsurface micro-irrigation systems, i.e., subsurface drip irrigation (SSDI), controlled surface irrigation (CSI), and surface drip-irrigation methods (SDI), with different irrigation water regimes, i.e., 50%, 75%, and 100% irrigation water requirements (IWRs), on the yield and fruit quality of date palms (cv. Khalas) and water conservation in the dryland region of Al-Ahsa, Saudi Arabia. The effects of three irrigation methods and IWRs were studied on macronutrients and soil chemical properties at three depths (0–30, 30–60, and 60–90 cm), as well as on water productivity, yield, and the fruit quality of date palms. The study was carried out over two years and was designed using a two-factorial randomized complete block design (RCBD) with nine replications. The results indicated that electrical conductivity (EC) increased as the depth of the soil increased. The soil chemical properties did not change much in all experimental treatments, while soil pH values decreased with the soil depth from 0–30 to 60–90 cm. Although the maximum fruit yield (96.62 kg palm^{-1}) was recorded when 100% irrigation water was applied in the SSDI system, other treatment combinations, such as SDI at 100% IWR (84.86 kg palm^{-1}), SSDI at 75% IWR (84.84 kg palm^{-1}), and CSI at 100% IWR (83.86 kg palm^{-1}) behaved alike and showed promising results. Similarly, the highest irrigation water productivity (2.11 kg m^{-3}) was observed in the SSDI system at 50% IWR, followed by the SSDI at 75% IWR (1.64 kg m^{-3}) and 100% IWR (1.40 kg m^{-3}). Fruit quality attributes were also promoted with the SSDI system at 75% IWR. Hence, the SSDI method at 75% IWR appeared to be an optimal choice for date palm irrigation in arid areas due to its positive impact on water conservation and fruit characteristics without affecting soil chemical properties.

Keywords: subsurface drip irrigation (SSDI); surface drip irrigation (SDI); controlled surface irrigation (CSI); water requirement; Khalas; time-based irrigation scheduling

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1. Introduction

Date palm, citrus, olive, grape, mango, and guava are the major fruits grown in the Kingdom of Saudi Arabia. Among them, the date palm contributes 57% to total fruit production and is cultivated in 63% of fruit-growing areas. It is cultivated on 152,705 ha, with an annual production of 1,541,769 tonnes. Globally, date palm is cultivated on 1,248,001 hectares, producing yields of 9,612,884 tonnes per year [1]. In arid and semi-arid regions, it is one of the main crops, providing food, nutrition, and building materials to the inhabitants [2,3]. However, the date palm growing areas are associated with limited water resources [4,5]. Despite the water shortage in these areas, water is applied inefficiently to the fields, causing groundwater to be depleted [6,7]. Changes in the soil environment directly impact crop growth and production [8]. Therefore, it is necessary to supplement soil moisture to maintain crop growth using various methods, the most significant of which is irrigation. The system of irrigation used in arid and semi-arid areas is critical in determining agriculture's long-term sustainability [9]. Water-saving agriculture technologies need to be adopted in the dryland regions to alleviate water shortages. Among the various options for water conservation, the use of suitable irrigation systems offers a feasible solution to inefficient water usage [10].

Due to its desert environment, Saudi Arabia is highly exposed to the negative consequences of climate change. The temperature in Saudi Arabia is predicted to rise by 6 °C by 2100 due to climate change [11,12]. Consequently, for 1 and 5 °C increases, crop irrigation water requirements will rise by ca. 602 and 3122 million m^3, respectively, and predicted yields of different crops will suffer losses ranging from 5 to >25% [11]. Therefore, effective technology transfer and modern research are necessary to use irrigation water sensibly for agricultural productivity in water-scarce areas [13]. Although utilizing large amounts of water with traditional irrigation methods supports the highest date palm productivity, innovative irrigation technologies can achieve the same tree yield with $\geq$50% less water [14–16].

Date palm thrives in water-scarce regions, but it requires adequate irrigation to maintain all metabolic processes to produce high-quality fruits [17,18]. As dates are a staple crop in the dryland area, increasing food production with less water will be a key concern in the following decades, especially in countries with limited water resources and poor water usage [19]. Modern irrigation methods have made it possible to conserve water and maximize water productivity in arid and semi-arid environments, which is critical for long-term crop production [20]. To figure out how much water date palm requires, studies have been undertaken in various regions of Saudi Arabia. For 100 palms ha^{-1}, one study recommended 7298.9 to 9495.2 m^3 ha^{-1} water [21], while other research recommended 7300 m^3 ha^{-1} [22]. Basin, border, and traditional furrow and flood irrigation systems are widely adopted to water orchards and field crops, including date palm in Saudi Arabia. As a result, the whole soil surface is practically flooded without considering the crops' precise requirements [19]. As a result of these practices, waterlogging and salinity have increased, resulting in decreased total irrigation efficiency [23,24]. Traditional irrigation practices are not only unsustainable, they also put excessive stress on already scarce water supplies [25]. Drip, bubbler, and sprinkler irrigation systems are among the many other surface irrigation methods used in crop production, most of which waste a significant amount of water [19,26].

On the other hand, surface drip irrigation has higher water productivity than other surface irrigation techniques, resulting in higher crop yields [27]. It uniformly distributes water and reduces soil erosion, labor costs, and the risk of plant diseases. It can also be operated at a lower pressure than conventional pressurized irrigation methods, resulting in energy savings [28]. The yield of drip-irrigated palms was found to be higher than that of sprinkler-irrigated trees [29]. The system outperforms sprinkler and surface irrigation methods [30]. Crops irrigated through a drip irrigation system produce a higher yield and more balanced soil moisture in the active root area with the least water loss [31,32].

In comparison to flood irrigation systems, surface drip irrigation saved 70–80% water and enhanced tomato yields by 22% per hectare [33]. However, while drip irrigation is being recommended in many countries to conserve water, its use in desert regions is controversial because it does not protect water from evaporation [34]. Therefore, modern and efficient irrigation systems are required in water-scarce regions to conserve water without compromising crop productivity and quality [35,36].

Subsurface drip irrigation could be used as an alternative to the surface drip technique. This method is characterized by applying water beneath the soil surface by drippers that distribute it at rates similar to surface drip irrigation [37]. It is the micro-irrigation system that has been used in agricultural irrigation for decades in many parts of the world. It is growing faster because it conserves water and improves crop yields better than surface drip irrigation [38,39]. Subsurface drip irrigation reduces subsurface drainage, manages soil salinity, and enhances tomato yield [40]. In addition, it is not affected by high wind velocity as the water is applied directly to plants' root zones [41,42]. Higher crop yields, saving of water, increased fertilizer use efficiency, reduced energy consumption, tolerance to windy atmospheric conditions, reduced labor cost, minimized pest and disease problems, suitability in sloppy lands, and improved soil tolerance to salinity are just a few advantages of subsurface drip irrigation system over other irrigation methods [10,29,41–46]. Although traditional surface irrigation systems produce the highest date palm yields by consuming more water [29,47], modern micro-irrigation systems can use less irrigation water and produce comparable yields [41,42]. To improve date palm irrigation management, an automated subsurface irrigation system was developed that was managed by a cloud based IoT system. The novel subsurface irrigation system increased date palm yield and water productivity [15]. It was also revealed that, compared to bubbler and drip irrigation systems, crop water productivity was significantly higher in subsurface irrigation systems at 50% ETc, which saved water and positively improved the physiological and fruit yield-related attributes of date palm cvs. Sheshi and Khalas [41,42].

The following were the study's key objectives: to evaluate the performance of the modern subsurface drip irrigation system and compare it with controlled surface irrigation and surface drip irrigation systems given different irrigation water requirements (IWRs); and to examine the effects of three irrigation systems given three IWRs on soil properties, IWP, tree yield, and fruit quality of the date palm cv. Khalas.

2. Materials and Methods

2.1. Experimental Site

The present research was conducted at the Julayjlah experimental farm (25°30′91″ N, a longitude of 49°35′59″ E, and an altitude of 160 m above MSL) at Al-Ahsa Irrigation and Drainage Authority, Eastern Region, Kingdom of Saudi Arabia (Figure 1). The experiment was conducted for two successive years (2018/2019 and 2019/2020). The investigation began immediately after harvest (1 October) and lasted through the end of September in each experimental year. The data was collected and analyzed from the experimental site to assess the effects of micro-irrigation systems with different irrigation water regimes on 25-year-old fully-grown, uniform, and healthy date palm cv. Khalas trees. All agricultural operations to serve palm trees were carried out in accordance with Alamoud et al.'s [48] recommendations at appropriate times.

2.2. Meteorological Conditions

For the two experimental years (2018/2019 and 2019/2020), Table 1 displays the average monthly data of the meteorological parameters of the experimental location from the weather station.

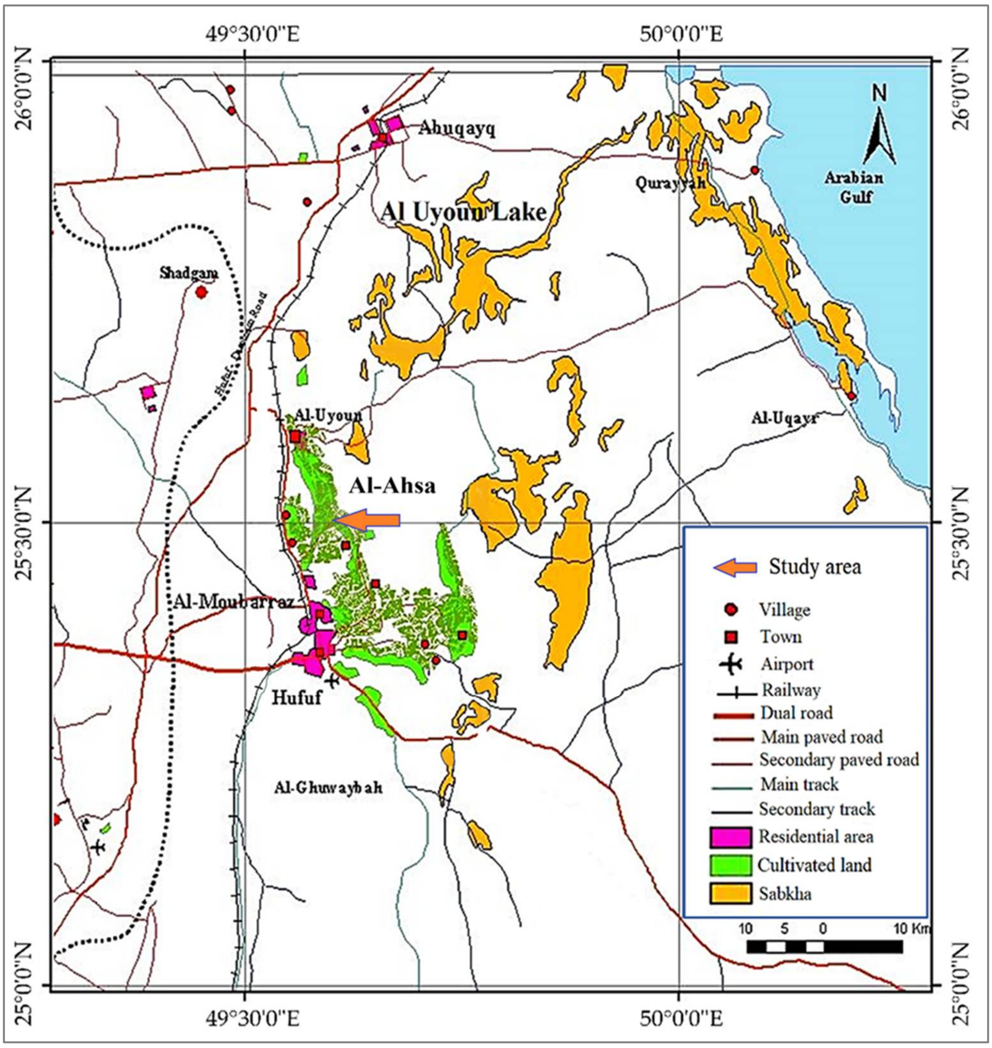

Figure 1. The location map of the experimental site [49].

Table 1. Average monthly values of the minimum temperature (Min T), maximum temperature (Max T), average relative humidity (Avg. RH), average wind speed (Avg. WS), average sunshine hours (Avg. SH), and average solar radiation (Avg. Rad) during the two years (2018/2019 and 2019/2020). The ± values indicate the standard deviation within means.

Months	Meteorological Parameters					
	Min T (°C)	Max T (°C)	Avg. RH (%)	Avg. WS (km day^{-1})	Avg. SH (h)	Avg. Rad (MJ m^{-2} day^{-1})
January	10.2 ± 3.3	24.1 ± 4.1	60.9 ± 28.3	192 ± 20.9	8.01 ± 0.2	16.3 ± 0.8
February	11.6 ± 2.4	25.9 ± 2.9	81.2 ± 19.7	151 ± 24.4	7.91 ± 0.1	18.1 ± 0.7
March	14.8 ± 3.6	29.4 ± 3.1	59.9 ± 22.6	173 ± 16.5	7.51 ± 0.1	22.1 ± 0.9
April	20.2 ± 3.8	35.3 ± 4.3	56.4 ± 19.6	194 ± 14.9	9.99 ± 0.1	23.1 ± 0.7
May	25.4 ± 3.5	42.9 ± 2.9	40.2 ± 14.3	173 ± 25.5	9.91 ± 0.2	23.2 ± 1.1
June	28.1 ± 2.8	46.8 ± 2.8	38.4 ± 19.6	199 ± 18.9	7.57 ± 0.2	23.9 ± 0.9
July	30.2 ± 3.8	47.3 ± 2.8	49.3 ± 19.8	197 ± 21.3	10.2 ± 0.2	26.6 ± 0.8
August	30.8 ± 2.9	46.8 ± 3.4	63.1 ± 21.3	191 ± 29.1	10.1 ± 0.1	25.9 ± 1.1
September	27.2 ± 2.8	43.9 ± 2.1	61.8 ± 19.6	183 ± 24.1	10.1 ± 0.2	23.6 ± 1.1
October	23.1 ± 3.2	39.3 ± 3.1	67.3 ± 18.2	183 ± 19.9	9.71 ± 0.2	23.1 ± 0.9
November	16.9 ± 4.2	31.1 ± 2.7	77.5 ± 21.2	182 ± 18.3	8.11 ± 0.2	20.3 ± 0.8
December	11.9 ± 5.3	23.8 ± 3.1	78.3 ± 22.4	201 ± 20.1	8.01 ± 0.2	15.3 ± 0.8

2.3. Description of Irrigation Systems

The irrigation systems' experimental setup included a water source and water tanks, water pump (3 kW), manual valves, a pressure regulator and pressure gauge, electrical solenoid valves, an irrigation network, a digital flow meter (Model: K24-S, SUNNY, Yantai, China), and a control system. The schematic diagram (Figure 2) shows the SSDI (Figure 2A), SDI (Figure 2B), and CSI (Figure 2C) irrigation systems installed around each date palm tree. The systems' surface and subsurface irrigation networks were implemented to operate automatically through the irrigation controller and electrical solenoid valves to supply each treatment with the calculated quantities of irrigation water (L palm^{-1} day^{-1}). The irrigation was scheduled according to the amount of water required for each treatment (three palm trees) under each irrigation system and irrigation water regime using three outdoor irrigation controllers (Model: Hunter XC-6, Hunter Industries, Inc., San Marcos, CA, USA). Each controller was set with the operating program for each irrigation system, expressed in the operating time, which is commensurate with the irrigation method network for each system and the amount of IWR for each treatment. The electrical solenoid valves were switched on/off at a specific time for the operation. According to the established irrigation scheduling, the operating signal was taken from the irrigation controller on which the irrigation program was set for the irrigation system. Based on the set-point irrigation water schedule, electrical solenoid valves were utilized to manage water flow for each date palm tree. High-density polyethylene was used to construct the irrigation network, including the mainline, sub mainline, and feeder ring pipe. A screen filter was used to filter the irrigation water before entering the irrigation network to prevent impurities or anything else that might affect the driplines and bubblers emitters.

The pressure in the irrigation network and water flow were controlled using the preassembled control zone kit produced by Rain Bird (Model: XCZLF100PRF, Rain Bird Corporation, Tucson, AZ, USA) that optimized for the lowest flow (Figure 3). The control zone kit included a low-flow solenoid valve (0.8 to 37.85 L m^{-1}) combined with a large capacity disc filter and high flow pressure regulator (the inlet pressure from 140 to 1030 kPa; the regulated pressure was 210 kPa). It was made specifically to provide filtration, on/off control, and pressure regulation for micro-irrigation systems.

In the SSDI system, a subsurface dripline (16 mm diameter and 1.2 mm thickness) included subsurface pressure-compensating (SSP-C) emitters with a distance between two SSP-C emitters of 0.457 m (Model: XFS-09-18-500, Rain Bird Corporation, Tucson, AZ, USA). Two lateral rings of subsurface dripline were installed around the date palm tree to provide irrigation coverage for the projected canopy of the date palm tree (Figure 2A). The inner lateral ring was 1.2 m in diameter, containing eight SSP-C emitters (the distance between two SSP-C emitters was 0.457 m). The outer lateral ring was 1.84 m in diameter, containing twelve SSP-C emitters. Thus, twenty SSP-C emitters were used for each date palm tree. The emitters provided a consistent flow in the irrigation network, ensuring higher uniformity and increasing irrigation reliability in the pressure range of 58–414 kPa. At a pressure of 210 kPa, each emitter delivered 3.5 L h^{-1} of flow. The twenty SSP-C emitters produced a total flow rate of 70 L h^{-1} for each date palm tree. The low-profile emitter design reduced the in-line pressure loss and allowed the subsurface driplines to irrigate nine-date palm trees with the same flow rate at the same time. The SSP-C emitters of the subsurface dripline were characterized by protection from root intrusion by Rain Bird's Copper Shield™ technology (Rain Bird Corporation, Tucson, AZ, USA). It also resists clogging using the extra-wide flow path combined with self-flushing and resists algae growth and chemical damage. Therefore, the SSDI system did not need maintenance during the experiment or replacement to prevent root intrusion. Based on Rain Bird Corporation's recommendation, dripline pipes were buried 0.2 m below the soil surface.

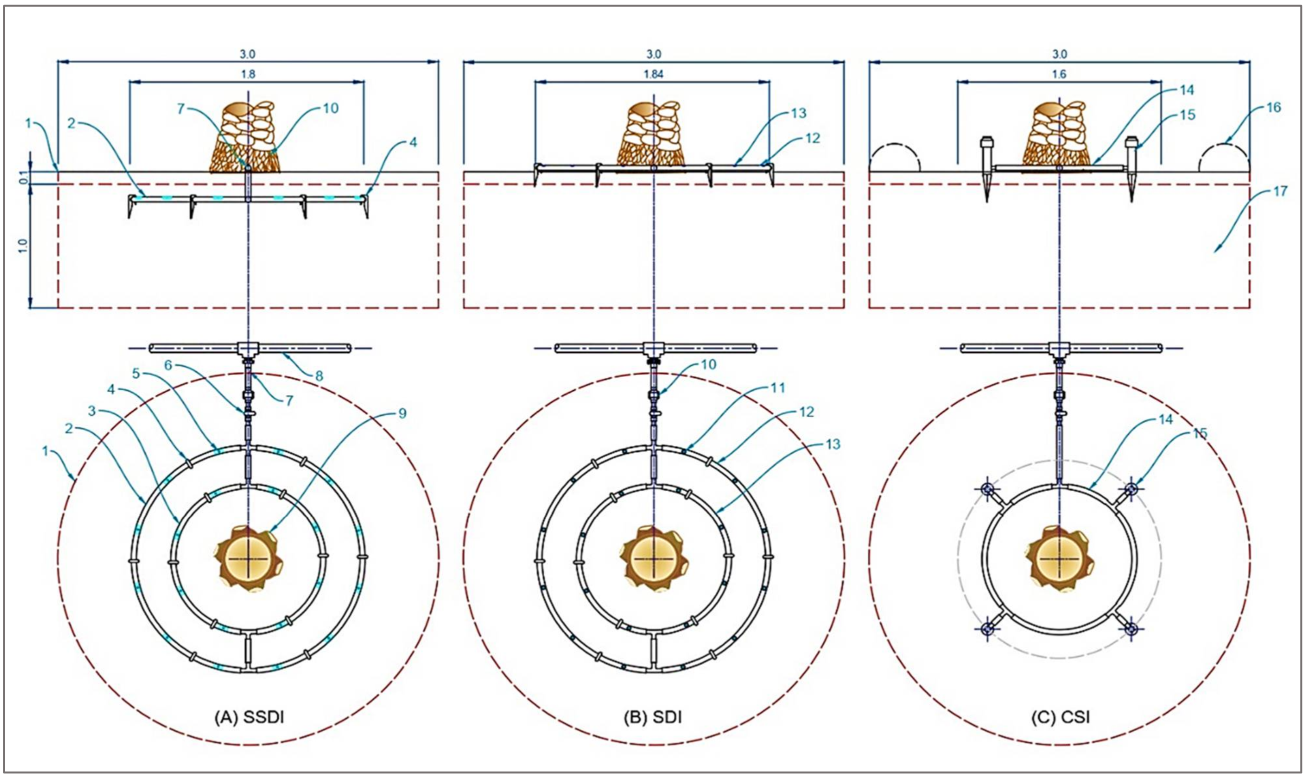

Figure 2. Layout of the main components of the (**A**) subsurface drip irrigation (SSDI), (**B**) surface drip irrigation (SDI), and (**C**) controlled surface irrigation (CSI) distribution around date palm trees. (1) Limits of the target area, (2) Subsurface dripline outer lateral ring, (3) Subsurface dripline inner lateral ring, (4) Tie-down stakes, (5) Subsurface pressure-compensating emitter, (6) Manual valve, (7) Dripline supply header, (8) Sub-mainline, (9) Date palm tree, (10) Digital flow meter, (11) Surface pressure-compensating emitter, (12) On-surface dripline outer lateral ring, (13) On-surface dripline inner lateral ring, (14) Bubbler lateral ring, (15) Pressure-compensating bubbler, (16) Contour line, and (17) Irrigation target zone.

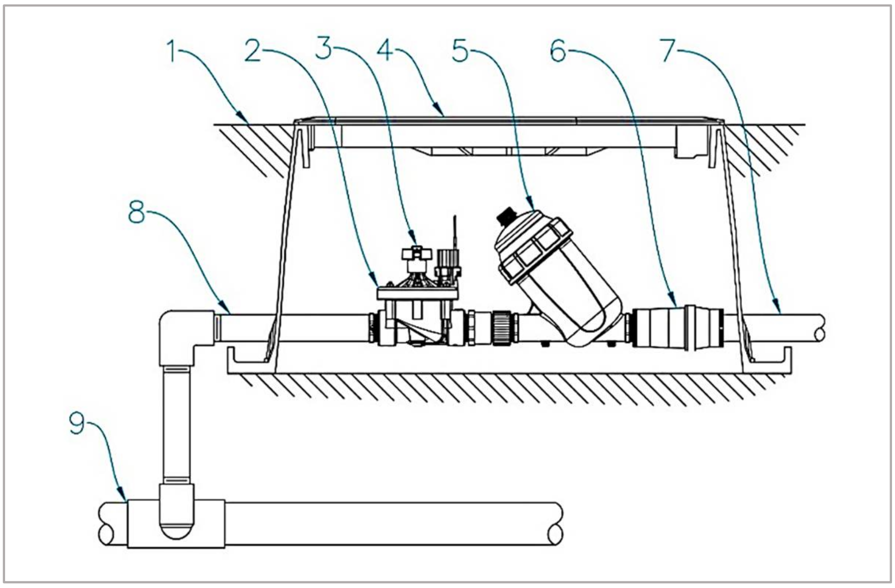

Figure 3. The control zone kit. This was in a covered plastic box that included a low-flow solenoid valve combined with a pressure-regulating filter. (1) Soil level, (2) Solenoid valve, (3) Regulator head, (4) Jumbo valve box with cover, (5) Large capacity disc filter, (6) High-flow pressure regulator, (7) Lateral pipe output, (8) Lateral pipe input, and (9) Main line pipe.

The on-surface driplines (16 mm diameter and 1.2 mm thickness) were used in the SDI system. Two lateral rings of on-surface dripline including SSP-C emitters with a distance between two SSP-C emitters of 0.457 m (Model: XFD-09-18-500, Rain Bird Corporation, Tucson, AZ, USA) were installed around the date palm tree. The rings provided irrigation coverage for the target area, as shown in Figure 2B. The diameters, flow rate, and number of emitters of the two on-surface driplines' lateral rings were as described for the SSDI. The installation of the two-lateral subsurface/on-subsurface dripline rings was conducted according to Rain Bird Corporation specifications and design guidelines for recommended spacing between rings.

In the CSI system, three pressure-compensating threaded bubblers (Model: PCT-05, Rain Bird Corporation, Tucson, AZ, USA) with a flow rate of 18.93 L h^{-1} were installed around the date palm tree for irrigation (Figure 2C). The total flow rate of the four bubblers was 75.72 L h^{-1} for each date palm tree at a pressure of 210 kPa. In addition, a contour line 0.25 m high and 2 m in diameter was made around each date palm tree to prevent water runoff.

2.4. Experimental Layout

The study was performed to determine the impact of the irrigation systems with different irrigation water regimes on the soil properties, water productivity, yield, and fruit quality of date palms (cv. Khalas). The time-based scheduling method was used in this study with the digital irrigation controller since it is considered an essential tool that significantly facilitates irrigation scheduling decisions for irrigation water conservation. Three micro-irrigation systems (SSDI, SDI, and CSI) and three irrigation water regimes (50%, 75%, and 100%) were included in the present study. The experiment was laid out according to the two-factorial randomized complete block design (RCBD). The first factor comprised three irrigation methods (SSDI, SDI, and CSI), and the second factor was the three irrigation water regimes (50%, 75%, and 100%). The total number of date palm trees included in the present experiment was eighty-one (three irrigation systems × three irrigation water regimes × nine replications). The layout of the experimental design is presented in Figure 4.

The irrigation water requirement was determined based on the target area and the calculated crop evapotranspiration (ET_c). The targeted irrigation area was set at 95% of the date palm trees' average shaded area. Based on the light intercepted fraction by its canopy, the shaded area of the date palm tree was calculated. The following relations were used to determine the irrigation water requirement:

$$IWR = \frac{ET_c \times A}{1000} \tag{1}$$

$$ET_c = k_c \times ET_o \tag{2}$$

$$ET_o = \frac{0.408\Delta(R_n - G) + \left(\gamma \frac{900}{T+273}\right) u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where IWR represents the irrigation water requirement (m^3 $palm^{-1}$), A represents the target irrigation area, ET_c is the evapotranspiration of the crop (mm day^{-1}), k_c is the crop factor (0.90), ET_o is the reference evapotranspiration of the experimental site (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (km s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope vapor pressure curve (kPa $°C^{-1}$), and γ is the psychrometric constant (kPa $°C^{-1}$).

A weather station (WS-PRO2, Rain Bird Corporation, Tucson, AZ, USA) was used to acquire the metrological data. The weather station included the highest quality sensors for measuring the minimum and maximum air temperature, solar radiation, relative humidity, rainfall, and speed and direction of the wind. Even in the severe environmental conditions of the research area, the sensors recorded and retained reliable data.

2.5. Irrigation Water Productivity

IWP was calculated using the following equation based on the date palm tree yield and the total irrigation water used:

$$IWP = \frac{Y}{I_r} \quad (4)$$

where *IWP* is the irrigation water productivity (kg m^{-3}), I_r is the irrigation water used per annum (m^3), and *Y* is the total yield (kg).

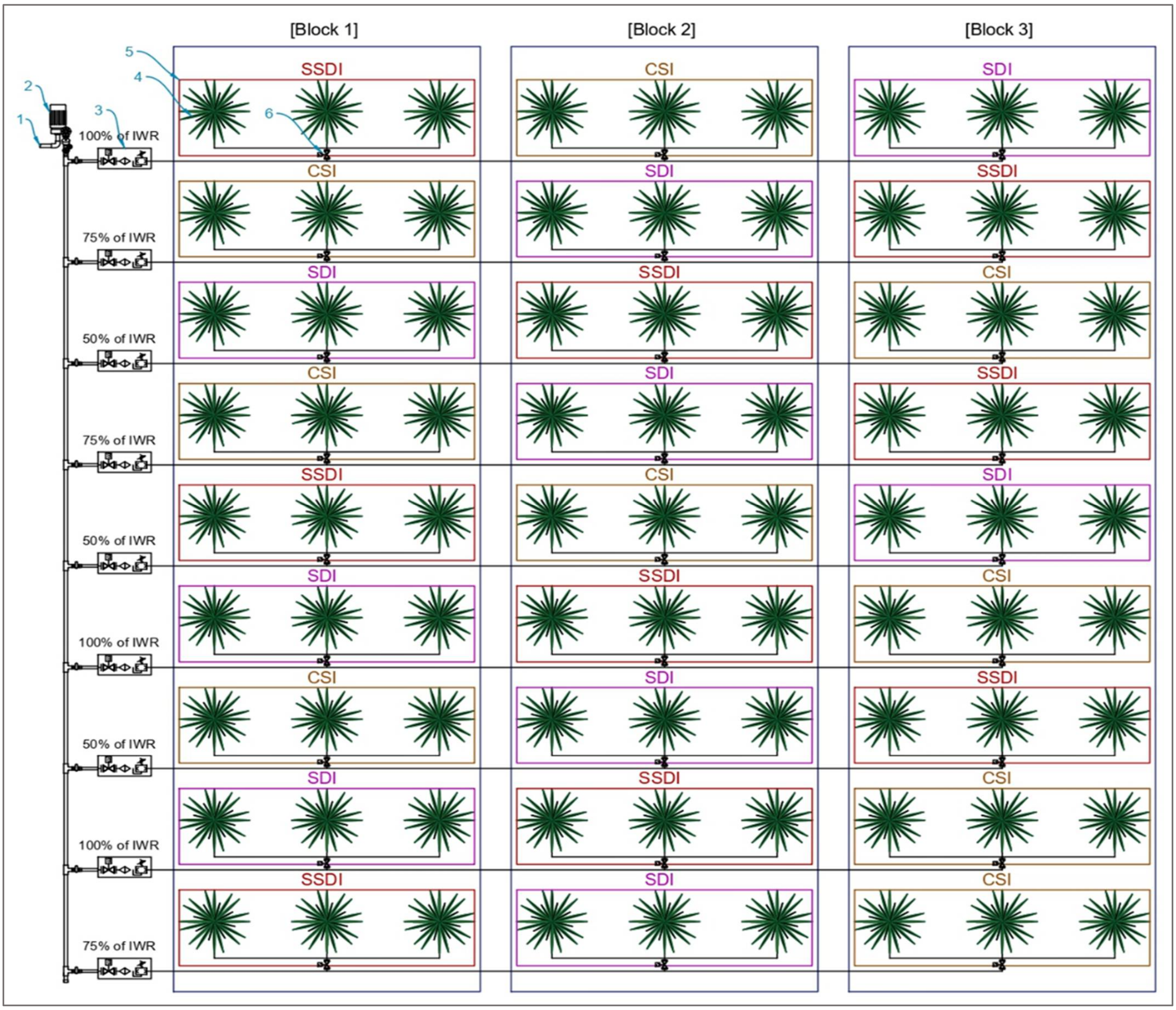

Figure 4. Layout of the experimental irrigation design. (1) Water source from water tanks, (2) Water pump with automatic water regulator, (3) Control zone kit, (4) Date palm tree, (5) Treatments, and (6) Electrical low-flow solenoid water valve.

2.6. Physicochemical Properties of the Soil

The soil samples analysis was conducted using sodium hexametaphosphate as a dispersing agent [50]. Pressure membranes were used to measure soil field capacity, moisture content, and permanent wilting point at 1–15 bar pressure [51]. The difference in soil water content between field capacity and the permanent wilting point was used to assess available water. The organic matter content was determined using the Walkley and Black rapid titration method [52]. For the estimation of electrical conductivity (EC), total dissolved salts (TDS), pH, soil saturation paste, and soil solution extraction were prepared according to the method of [53]. The EC (dS m^{-1}) and TDS (mg L^{-1}) were estimated in the soil paste extraction using a conductivity meter, temperature compensating type (Model: HQ1140, Hach Company, Loveland, CO, USA) [54]. Soil pH was determined in soil pastes (suspensions) using a pH meter (Model: HQ411D, Hach Company, Loveland, CO, USA) [50]. Soluble carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were estimated by titration of soil extract with HCl using phenolphthalein and methyl orange as indicators, respectively [53]. Soluble chloride was determined using a standard solution of silver nitrate in the presence of potassium chromate as an indicator. The difference between the concentrations of total dissolved cations and anions concentration in meq L^{-1} was used to determine soluble sulfate [54]. Magnesium and soluble calcium were determined using EDTA (Versenate) solution in the presence of ammonium purpurate as an indicator for estimating calcium and eirochrome black-T as an indicator for estimating calcium and magnesium [54]. Sodium and potassium were measured using a flame photometer (Model: BWB XP, BWB Technologies Ltd., Newbury, Berkshire, UK) in a saturation-paste soil extract [52]. Carter's methods were used to calculate the exchangeable sodium percentage (ESP) [55]. Mineral nitrogen was extracted using 2.0 M KCL as an extracting solution in a 1:5 ratio and determined using Keeney and Nelson's technique [56]. Available phosphorus in soil extract was extracted using Olsen solution and determined using ammonium molybdate, ascorbic acid, and a small quantity of antimony, which was quantified using a spectrophotometer (Model: UV/VIS Spectrophotometer, Mettler Toledo, Columbus, OH, USA) at 882 nm wavelength. A 1.0 N ammonium acetate solution was used to extract available potassium, which was then measured using a flame photometer (Model: BWB XP, BWB Technologies Ltd., Newbury, UK).

2.7. Chemical Properties of Irrigation Water

The pH, EC, TDS, sodium adsorption ratio (SAR), residual sodium carbonate (RSC), soluble sodium percentage (SSP), potential salinity, soluble magnesium percentage (SMgP), soluble cations and anions, and micronutrients of irrigation water were determined using analytical methods described by Richards [50], Ayers and Westcot [57], Kovda et al. [58], and FAO [59,60].

2.8. Fruit Quality Parameters

One-hundred randomly selected Tamar fruit samples from each experimental replicate were taken, and the following physical properties were measured: fruit weight (gm) and size (mm), pulp and seed weight (gm), and pulp/seed ratio [61–63]. A digital Vernier caliper was used to measure the length and diameter of the fruit. An electronic balance was used to determine the weight of the pulp and seed (Sartorius Lab Instruments GmbH and Co., Göttingen, Lower Saxony, Germany). The fruit quality parameters, such as moisture content, total soluble solids, total sugars, reducing sugars, and non-reducing sugars, were determined according to AOAC standard methods [64].

2.9. Statistical Analysis

The analysis of variance (ANOVA) of the data of the present study was calculated using the SPSS statistical program (SPSS Inc., Chicago, IL, USA). The Tukey test was used to evaluate whether there was a significant difference between the treatment means at 5% significance level ($p < 0.05$).

3. Results and Discussion

3.1. Irrigation Water Quality

The data in Table 2 indicate that the mean value of EC_{iw} of irrigation groundwater (GW) was 2.78 dS m^{-1}, which is not very detrimental for date palm tree growth. The critical level of EC_{iw} value of 3 dS m^{-1} was suggested to cause salinity problems for date palms [60]. Some date palm cultivars can withstand salinity levels as high as 12.8 dS m^{-1} [65], while others can only withstand mild salinity (between 4 and 10 dS m^{-1}) [66,67]. Despite the wide variation in salt tolerance across cultivars, date palm is usually thought to be a salt-tolerant species [65–67]. Table 1 further demonstrated that irrigation water's SAR value was reasonably low (4.25) when compared to the critical limit of sodium hazard (<10), as stated by Richards [50]. Similarly, the value of SSP (40.56%) was also less than the critical level (<60%), as stated by Wilcox [68]. Magnesium hazard is one of the parameters for the suitability of irrigation water. In this respect, the mean value of SMgP indicated that the quality of irrigation water has a value of 33.78%, which is less than the harmful level (>50%). It indicated that there is no hazard of magnesium salt toxicity. The RSC value evaluates the movement of irrigation water to produce carbonates, precipitate calcium, and dissolve magnesium carbonates to a moderate degree. The precipitation of weakly soluble carbonates raises the sodium hazard of irrigation water, which raises the sodality of irrigated soil. The present value of RSC has a negative value (−9.21 mg L^{-1}). This means that Ca^{++} and Mg^{++} are more than the CO_3^{--} HCO_3^- which indicated no hazard issue of sodium. The potential salinity for irrigation water used is 25.65 mg L^{-1}. The high PS values over the critical level (5 meq L^{-1}) could be attributed to the irrigation water's excessive chloride and sulfate content [50]. Chlorine, on the other hand, was very high (21.46 mg L^{-1}), according to the water quality recommendations [60]. The concentration of boron in irrigation water was 0.19 mg L^{-1}. The palm trees are considered semi-tolerant to boron toxicity. However, its toxic range in irrigation water is 1–2 mg L^{-1} (Wilcox, 1958). Therefore, the water applied in the present study was boron toxicity-free. The nitrate contents (NO_3^-) in the irrigation water (4.02 meq L^{-1}) did not exceed the critical limit (45 mg L^{-1}) that causes nitrate poisoning [68]. Hence, the overall quality of irrigation water applied in the present study was quite suitable for date palm growth and posed no toxic hazard.

3.2. Applied Irrigation Water

Figure 5 depicts the average monthly IWR and the average quantity of cumulative water per palm over the study years under three irrigation water regimes (50%, 75%, and 100%). The *ETc* ($ET_c = k_c \times ET_o$) and the date palm trees' irrigation targeted area were used to calculate the average monthly irrigation water requirement. The Penman–Monteith equation was used to determine the ET_o. During the date palms' productive cycle, the average k_c value was 0.95. The date palm trees' average targeted area was 28.52 ± 2.13 m^2. The average values of the actual water applied per date palm tree did not differ significantly across the assessed irrigation systems (SSDI, SDI, and CSI). During 2018/2019 and 2019/2020, the average cumulative irrigation water consumption under different irrigation water regimes (50%, 75%, and 100% IWR) was 34.42 ± 0.15, 51.63 ± 1.68, and 68.83 ± 1.24 m^3 $palm^{-1}$, respectively.

3.3. Physicochemical Properties of the Soil

To determine the physicochemical properties of the experimental orchard, soil samples were collected at three soil depths (0–30, 30–60, and 60–90 cm). Table 3 shows the soil physical properties of the experimental orchard. The methodological procedures were followed as described by Page et al. [53] and Klute [51].

Table 2. Chemical analysis of the irrigation water quality applied.

Chemical Properties		Mean Values
pH		7.48
EC (dS m^{-1})		2.78
TDS (mg L^{-1})		17,778
SAR value		4.25
RSC (mg L^{-1})		−9.21
SSP (%)		40.56
Potential Salinity (PS mg L^{-1})		25.65
SMgP (%)		33.78
Soluble cations (meq L^{-1})	Ca^{++}	12.9
	Mg^{++}	6.85
	Na^{+}	13.3
	K^{+}	0.02
Soluble anions (meq L^{-1})	CO_3^{--}	0
	HCO_3^{-}	3.46
	Cl^{-}	21.46
	SO_4^{--}	8.4
	NO_3^{-}	4.02
Micronutrients (mg L^{-1})	Fe	3.69
	Mn	0.51
	Zn	0.2
	Cu	0.15
	Mo	0.006
	B	0.19

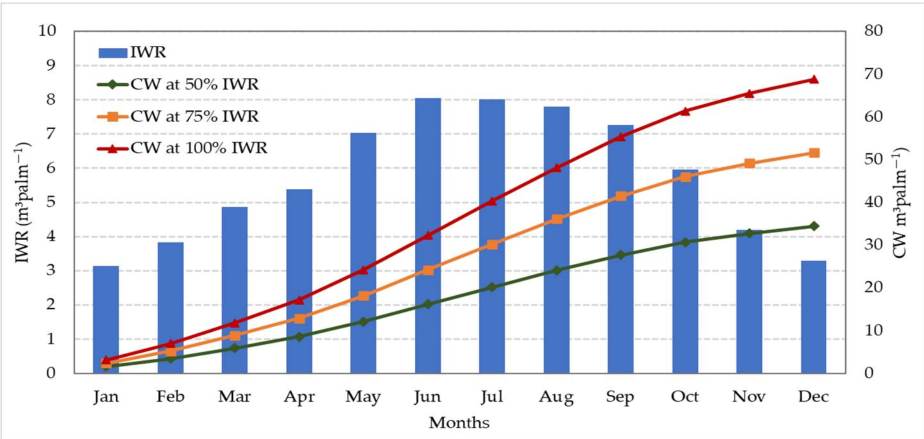

Figure 5. Average monthly irrigation water requirements (IWRs) and amounts of cumulative water (CW) palm^{-1} under three irrigation water regimes (50%, 75%, and 100% IWR) during 2018/2019 and 2019/2020.

The results in Table 4 showed that the EC values generally increased with the depth of the soil. At 60–90 cm depth, EC values were 3.00 (50% IWR), 2.93 (75% IWR), and 2.79 dS m^{-1} (100% IWR) when plants were irrigated by the CSI system. At the same soil depth, the EC values were 2.74 (50% IWR), 2.71 (75% IWR), and 2.57 dS m^{-1} (100% IWR) when plants were irrigated by the SDI system. However, the EC values were minimal when plants were irrigated by the SSDI system at the same soil depth (60–90 cm), i.e., 2.63 (50% IWR), 2.54 (75% IWR), and 2.62 dS m^{-1} (100% IWR). The increase in EC from the top layer of the soil to the bottom layer could be due to the downward movement of the dissolved salts in water from the top surface of the soil [69]. It was revealed that the soil pH values decreased with an increase of the soil layer depth from 0–30 cm to 60–90 cm under different irrigation methods and different IWRs. These findings are in accordance with those reported by Dahdoh and Hassan [70]. The results regarding soil OM showed that it was increased from 100 to 50% IWR at the top soil layer (0–30 cm) in all irrigation systems. However, it linearly decreased from the top (0–30 cm) to the bottom soil layers (60–90 cm) with all IWRs and irrigation systems. This may be due to the application of OM at the top soil layer, i.e., 0–30 cm. The OM is usually incorporated at the top soil layer, and soil microorganism activities are higher near the root zone [71,72]. In terms of soil cation concentrations, particularly Na^+, the concentration of Na^+ in the experimental soil irrigated by various irrigation systems increased with the soil depth. Similarly, the concentrations increased as IWRs decreased. The distribution of sodium cations through the soil layers was similar to the distribution of salts at different soil layers. These findings are likewise in line with those obtained by Al-Omran et al. [73]. A similar trend was recorded in ESP because of the increasing concentration of Na^+ in the soil layers. These results are in line with Abdel-Nasser et al. [69], who stated that increasing soil Na^+ concentration led to an increase in the ESP in the soil profile. Al-Omran et al. [73] reported similar results. Salt leaching options must be considered during irrigation to eliminate excess salt that accumulates in the soil to minimize the risks of salinity.

Table 3. Soil physical properties of the experimental orchard.

Soil Depth (cm)	Soil Particle Size (%)				SP (%)	FC (%)	PWP (%)	AW (%)	K_s	Bd (gm cm^{-3})
	Soil Texture	Sand	Silt	Clay						
0–30	Sandy Loam	80.25	8.31	11.44	37.33	18.37	9.40	8.97	8.57	1.54
30–60	Sandy Loam	82.40	7.00	10.6	39.67	18.67	9.83	8.84	9.03	1.57
60–90	Sandy Loam	82.95	6.74	10.31	38.33	17.10	9.20	7.9 B	8.00	1.62

Saturation percentage (SP), field capacity (FC), permanent wilting point (PWP), available water (AW), saturated hydraulic conductivity (K_S), and bulk density (Bd).

Table 4. Soil chemical properties of the experimental orchard.

Soil Properties	Soil Depth (cm)	Irrigation Methods								
		CSI			SDI			SSDI		
		100%	75%	50%	100%	75%	50%	100%	75%	50%
EC (dS m^{-1})	0–30	2.48	2.60	2.67	2.29	2.41	2.44	2.59	2.51	2.60
	30–60	2.75	2.89	2.96	2.54	2.67	2.70	2.34	2.27	2.35
	60–90	2.79	2.93	3.00	2.57	2.71	2.74	2.62	2.54	2.63
pH	0–30	7.78	8.17	8.36	7.17	7.55	7.63	7.32	7.10	7.35
	30–60	7.61	7.99	8.18	7.01	7.38	7.46	7.16	6.95	7.19
	60–90	7.47	7.84	8.03	6.89	7.25	7.33	7.03	6.82	7.06
OM (%)	0–30	0.36	0.38	0.39	0.33	0.35	0.35	0.34	0.33	0.34
	30–60	0.24	0.25	0.26	0.22	0.23	0.23	0.22	0.21	0.22
	60–90	0.14	0.15	0.15	0.13	0.14	0.14	0.13	0.13	0.13
Ca^{++}	0–30	10.38	10.90	11.16	9.57	10.07	10.18	9.77	9.48	9.81
	30–60	11.22	11.78	12.06	10.34	10.88	11.00	10.56	10.24	10.60
	60–90	12.25	12.86	13.17	11.29	11.88	12.01	11.53	11.18	11.57
Mg^{++}	0–30	1.55	1.63	1.67	1.43	1.50	1.52	1.46	1.42	1.47
	30–60	1.81	1.90	1.95	1.67	1.76	1.78	1.71	1.66	1.72
	60–90	2.05	2.15	2.20	1.89	1.99	2.01	1.93	1.87	1.94
Na^+	0–30	18.94	19.89	20.36	17.45	18.37	18.57	21.69	21.04	21.78
	30–60	23.05	24.20	24.78	21.24	22.36	22.61	17.82	17.29	17.90
	60–90	23.67	24.85	25.45	21.81	22.96	23.21	22.27	21.60	22.36
K^+	0–30	0.63	0.66	0.68	0.58	0.61	0.62	0.59	0.57	0.59
	30–60	0.71	0.75	0.76	0.66	0.69	0.70	0.67	0.65	0.67
	60–90	0.91	0.96	0.98	0.84	0.88	0.89	0.86	0.83	0.86

Table 4. *Cont.*

Soil Properties	Soil Depth (cm)	Irrigation Methods								
		CSI			SDI			SSDI		
		100%	75%	50%	100%	75%	50%	100%	75%	50%
HCO_3^-	0–30	8.89	9.33	9.56	8.19	8.62	8.71	8.36	8.11	8.39
	30–60	10.42	10.94	11.20	9.60	10.11	10.22	9.80	9.51	9.84
	60–90	11.00	11.55	11.83	10.14	10.67	10.79	10.35	10.04	10.39
Cl^{-1}	0–30	11.99	12.59	12.89	11.05	11.63	11.76	11.28	10.94	11.32
	30–60	13.64	14.32	14.66	12.57	13.23	13.38	12.83	12.45	12.89
	60–90	17.49	18.36	18.80	16.12	16.97	17.16	16.46	15.97	16.53
SO_4^-	0–30	10.63	11.16	11.43	9.79	10.31	10.42	10.00	9.70	10.04
	30–60	10.39	13.36	13.67	11.72	12.34	12.48	11.97	11.61	12.02
	60–90	11.08	10.91	11.17	9.58	10.08	10.19	9.78	9.49	9.82
SAR	0–30	12.90	11.63	11.91	10.21	10.75	10.87	10.42	10.11	10.46
	30–60	12.65	13.55	13.87	11.88	12.51	12.65	12.13	11.77	12.18
	60–90	13.12	13.28	13.60	11.66	12.27	12.40	11.90	11.54	11.94
ESP	0–30	13.09	13.74	14.07	12.09	12.73	12.87	12.34	11.97	12.39
	30–60	14.41	14.49	15.09	13.83	14.56	14.72	14.12	13.70	14.18
	60–90	15.01	15.31	15.62	13.28	13.98	14.13	13.56	13.15	13.61

The mean values of available N, P, and K (mg kg^{-1} soil) of the experimental orchard irrigated by three irrigation systems (CSI, SDI, and SSDI) under different irrigation regimes (50%, 75%, and 100% IWR) are shown in Figure 6. The results indicated that at 0–30 cm soil depth, the highest values of available N (21.18 mg kg^{-1}), P (11.77 mg kg^{-1}), and K (12.77 mg kg^{-1}) were noted in the CSI system at 75% IWR. However, the highest concentration of available N (25.21 mg kg^{-1}), P (11.17 mg kg^{-1}), and K (11.84 mg kg^{-1}) was estimated in the SDI system at 100% IWR at 0–30 cm soil depth. Similarly, the soil irrigated by the SSDI system had the maximum amount of available N (21.25 mg kg^{-1}), P (12.05 mg kg^{-1}), and K (13.64 mg kg^{-1}) at 75% IWR at a soil depth of 0–30 cm. This could be related to the mobility and distribution of irrigation water in the soil profile. These findings are consistent with those of Rafie and El-Boraie [74], who found that increasing the irrigation water application rate allows for more horizontal water distribution while decreasing the rate allows for more vertical water distribution. Only when the discharge rate was raised did a saturated zone form below the drip line at a distance of 20–25 cm from the water source. Several studies have investigated the effect of different irrigation systems on macronutrient distribution in the soil profile [69,75,76].

3.4. Yield and Water Productivity

The data in Table 5 revealed that the trees subjected to the SSDI system had the highest yield (84.68 kg palm^{-1}), followed by the CSI (55.39 kg palm^{-1}) and SDI (55.12 kg palm^{-1}) systems. On the other hand, the date palm trees that received 100% IWR had the highest fruit yield (88.45 kg palm^{-1}), followed by those receiving the 75% (68.68 kg palm^{-1}) and 50% (38.07 kg palm^{-1}) IWRs. The interaction of both factors indicated that the palm yield was maximum (96.62 kg palm^{-1}) when 100% irrigation water was applied in the SSDI system. Other treatment combinations, such as SDI at 100% IWR (84.86 kg palm^{-1}), SSDI at 75% IWR (84.84 kg palm^{-1}), and CSI at 100% IWR (83.86 kg palm^{-1}), behaved alike and showed promising results. Table 5 also shows that IWP was higher (1.72 kg m^{-3}) when the SSDI system was applied, followed by the CSI (1.01 kg m^{-3}) and SDI (0.99 kg m^{-3}) systems. The IWR at 75% had the maximum IWP (1.33 kg m^{-3}); however, IWRs at 100% and 50% had 1.28 kg m^{-3} and 1.11 kg m^{-3} IWP, respectively. The interaction data for both factors indicated that highest IWP (2.11 kg m^{-3}) was observed in the SSDI system at 50% IWR followed by the SSDI at 75% IWR (1.64 kg m^{-3}) and 100% IWR (1.40 kg m^{-3}). Our findings revealed that the increased yield was related to the SSDI system's optimal availability of soil water, which expedited stable root growth and improved the uptake of soil nutrients [77,78]. Palm yield was also improved by applying 65% of the total date palm water demand [22]. Highest fruit yield and crop water productivity was reported in date palm cvs. Sheshi [42] and Khalas [41] when the trees were irrigated by the subsurface irrigation system at 50% ETc. Another study found that the date palm plant irrigated with a 60% water requirement in the SSDI system showed no significant difference compared to the bubbler system at 100% ETc [79]. Similarly, the date palm yield was significantly enhanced when irrigation water was applied through the subsurface irrigation system compared to the SDI system [80]. Almost all of the water applied through the SSDI system is utilized by the plant through root extraction, as reported by Albasha [81]. Since evaporation and drainage losses are negligible and the wetted surface spreads across the entire root zone, the SSDI system is supposed to provide more stable water conditions that favor optimal root system growth [82]. Although the date palm can withstand prolonged abiotic stresses, including drought, long-term water stress significantly reduces tree growth and productivity [66,83,84].

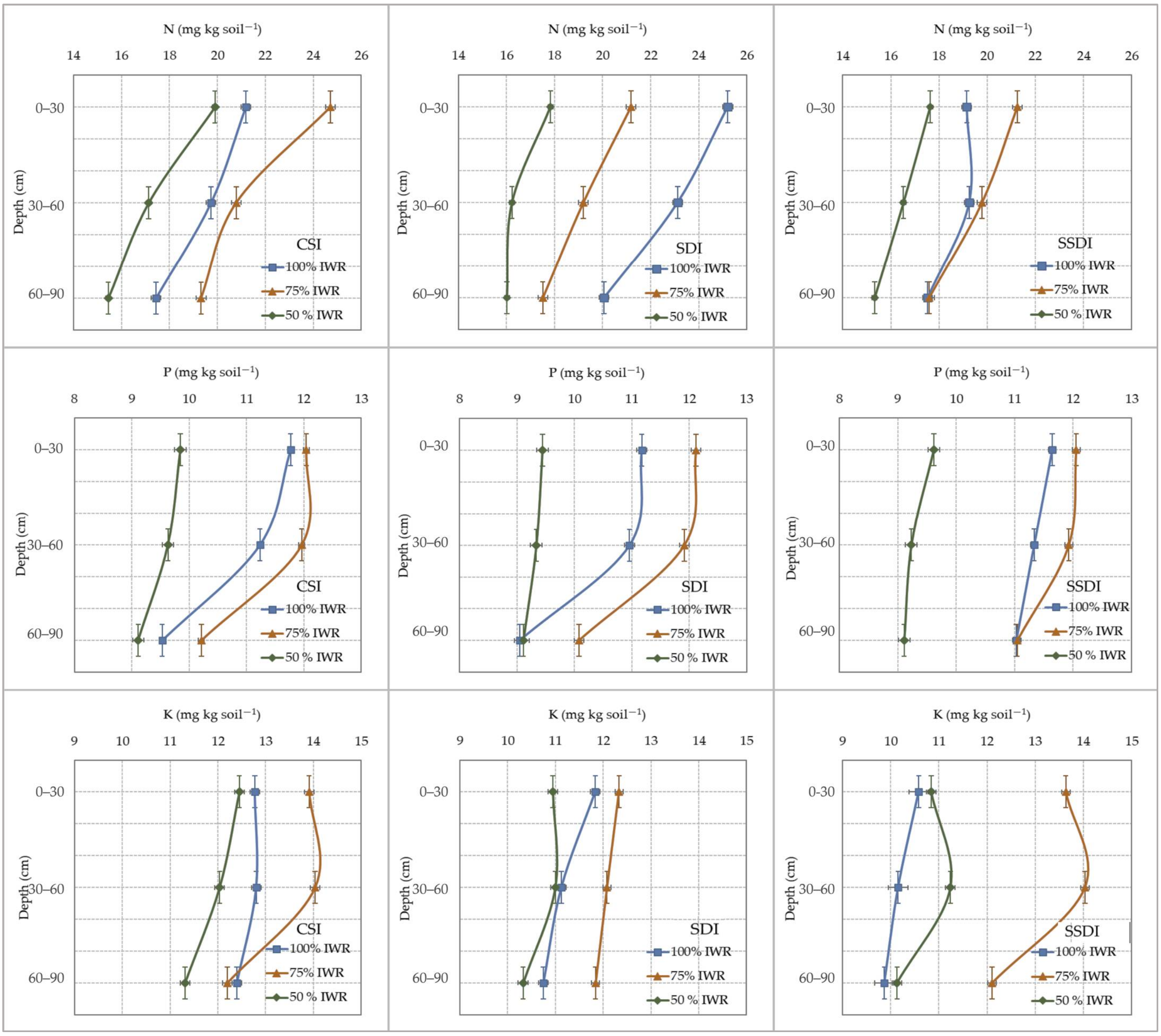

Figure 6. Available macronutrients, N, P, and K (mg kg^{-1} soil), in the experimental orchard's soil irrigated by different irrigation methods and different rates of IWR at different soil depths. Each data point indicates the mean values of two years (2018/2019 and 2019/2020).

Table 5. Effects of different irrigation methods (IMs) and irrigation water regimes (IWRs) on the yield (kg palm^{-1}) and irrigation water productivity (IWP) (kg m^{-3}) of date palm cv. Khalas during two years (2018/2019 and 2019/2020).

Factors	Treatments		Yield (kg palm^{-1})	IWP (kg m^{-3})
IM	CSI		55.39 ± 25.96 ^{b}	1.01 ± 0.27 ^{b}
	SDI		55.12 ± 27.81 ^{b}	0.99 ± 0.32 ^{b}
	SSDI		84.68 ± 10.18 ^{a}	1.72 ± 0.30 ^{a}
IWR	100% IWR		88.45 ± 6.35 ^{a}	1.28 ± 0.09 ^{b}
	75% IWR		68.68 ± 11.81 ^{b}	1.33 ± 0.23 ^{a}
	50% IWR		38.07 ± 25.13 ^{c}	1.11 ± 0.73 ^{c}
IM × IWR	CSI	100% IWR	83.86 ± 1.38 ^{b}	1.22 ± 0.02 ^{d}
		75% IWR	59.96 ± 1.93 ^{d}	1.16 ± 0.04 ^{d}
		50% IWR	22.35 ± 4.56 ^{e}	0.65 ± 0.13 ^{e}
	SDI	100% IWR	84.86 ± 3.83 ^{b}	1.23 ± 0.05 ^{d}
		75% IWR	61.23 ± 1.31 ^{d}	1.19 ± 0.02 ^{d}
		50% IWR	19.28 ± 3.65 ^{e}	0.56 ± 0.11 ^{e}
	SSDI	100% IWR	96.62 ± 1.11 ^{a}	1.40 ± 0.02 ^{c}
		75% IWR	84.84 ± 2.48 ^{b}	1.64 ± 0.05 ^{b}
		50% IWR	72.57 ± 2.01 ^{c}	2.11 ± 0.06 ^{a}

For each factor (IM and IWR) and their interaction (IM × IWR), means with the same letter are not significantly different at $p \leq 0.05$.

3.5. Physicochemical Properties of Date Palm Fruits

The date palm trees irrigated with the SSDI system produced maximum fruit length (32.63 mm), fruit width (20.53 mm), pulp weight (8.48 gm), seed weight (0.87 gm), and pulp/seed ratio (9.78) (Table 6). However, there was a non-significant difference regarding the fruit width (20.59 mm), pulp weight (8.66 gm), and seed weight (0.89 gm) parameters when the SSDI system was compared with the SDI system. There was also a statistically non-significant difference regarding the fruit weight variable in all three irrigation systems, i.e., 9.03 gm (SSDI and SDI) and 9.02 gm (CSI). On the other hand, date palm trees treated with 75% IWR had the maximum fruit length (34.51 mm), fruit width (21.38 mm), pulp weight (9.06 gm), and pulp/seed ratio (10.41). Trees treated with 100% IWR produced maximum fruit weight (9.78 gm) and seed weight (0.90 gm). The interaction of irrigation methods and IWR showed that the fruit length (36.81 mm), fruit width (22.43 mm), and pulp/seed ratio (11.37) was higher when 75% IWR was applied in the SSDI system. Other treatment combinations, such as SSDI at 100% IWR, SDI at 100% IWR, and SDI at 75% IWR, resulted in higher fruit weight (9.95 gm), pulp weight (9.83 gm), and seed weight (0.96 gm), respectively. The SSDI system enhanced total fruit quality metrics, according to the findings of this study. This could be attributed to the functional absorbing root zone's effective use of water. Plant nutrient uptake is likely enhanced and improved by proper water consumption within the tree system [42,77,78]. Changes in carbon allocation are usually triggered by a reduction in water absorption, which improves fruit growth and productivity [85]. Reduced irrigation water improved the physical characteristics of date palm fruit of cv. Mazafati [86]. These findings are in accordance with those of our current study. It is also reported that the fruit quality indices of date palm cvs. Sheshi [42] and Khalas [41] were significantly improved under subsurface irrigation systems at 50 and 75% ETc.

Moisture content (15.15%), TSS (52.90 Brix), total sugars (69.45%), reducing sugars (67.50%), and non-reducing sugars (1.95%) were significantly higher in the fruits of date palm cv. Khalas when irrigated with the SSDI system (Table 7). Similarly, date palm trees irrigated at 75% IWR had maximum TSS (53.35 Brix), total sugars (70.30%), and reducing sugars (68.64%). However, moisture content (14.89%) and non-reducing sugars (2.07%) were significantly higher at 100% IWR and 50% IWR, respectively. The interaction of irrigation methods and IWR revealed that the moisture content (17.13%) and non-reducing sugars (2.21%) were maximum in the SSDI system at 100% IWR, whereas total sugars (71.85%) and reducing sugars (70.33%) were higher in the SSDI system at 75% IWR. Other irrigation systems, such as CDI at 75% IWR and SDI at 100% IWR, had maximum TSS values, i.e., 54.47 and 54.46 Brix, respectively, and were statistically at par. These findings could be related to the functional absorbing root zone's effective usage of water. Plants grown under low water conditions had higher solute concentrations and accumulated more sugars, resulting in higher total soluble solids [87]. When date palms were subjected to a deep drip irrigation system, higher total soluble solids were recorded [88], which is similar to current findings.

Table 6. Effect of different irrigation methods (IMs) and irrigation water regimes (IWRs) on the physical properties of date palm cv. Khalas during two years (2018/2019 and 2019/2020).

Factors	Treatments		Fruit Length (mm)	Fruit Width (mm)	Fruit Weight (gm)	Pulp Weight (gm)	Seed Weight (gm)	Pulp/Seed Ratio
IM	CSI		31.65 c	20.05 b	9.02 a	7.83 b	0.83 b	9.43 c
	SDI		32.46 b	20.59 a	9.03 a	8.66 a	0.89 a	9.65 b
	SSDI		32.63 a	20.53 a	9.03 a	8.48 a	0.87 a	9.78 a
IWR	100% IWR		33.76 b	20.74 b	9.78 a	8.76 b	0.90 a	9.77 b
	75% IWR		34.51 a	21.38 a	9.14 b	9.06 a	0.87 b	10.41a
	50% IWR		28.47 c	19.05 c	8.16 c	7.15 c	0.82 c	8.67 c
IM × IWR	CSI	100% IWR	31.87 f	19.08 f	9.59 c	7.56 f	0.80 e	9.44 d
		75% IWR	34.55 c	21.61 c	9.20 d	8.95 d	0.84 cd	10.64 c
		50% IWR	28.25 h	18.75 i	8.28 g	6.97 i	0.85 c	8.21 h
	SDI	100% IWR	36.25 b	22.21 b	9.81 b	9.83 a	0.92 b	10.67 b
		75% IWR	32.18 e	20.12 e	9.09 f	8.98 c	0.96 a	9.23 e
		50% IWR	28.95 g	19.44 g	8.19 h	7.18 h	0.79 e	9.06 f
	SSDI	100% IWR	33.16 d	20.21 d	9.95 a	8.90 e	0.97a	9.21 e
		75% IWR	36.81 a	22.43 a	9.12 e	9.25 b	0.81 de	11.37 a
		50% IWR	27.93 i	18.96 h	8.10 i	7.29 g	0.83 ce	8.75 g

For each factor (IM and IWR) and their interaction (IM × IWR), means with the same letter are not significantly different at $p \leq 0.05$.

Table 7. Effect of different irrigation methods (IMs) and irrigation water regimes (IWRs) on the chemical properties of date palm cv. Khalas during two years (2018/2019 and 2019/2020).

Factors	Treatments	Moisture Content (%)	TSS (Brix)	Total Sugars (%)	Reducing Sugars (%)	Non-Reducing Sugars (%)
IM	CSI	13.29 b	52.78 b	68.73 b	66.90 b	1.82 c
	SDI	13.20 c	52.32 c	68.63 c	66.76 c	1.87 b
	SSDI	15.15 a	52.90 a	69.45 a	67.50 a	1.95 a
IWR	100% IWR	14.89 a	52.92 b	68.82 b	66.91 b	1.91 b
	75% IWR	12.88 c	53.35 a	70.30 a	68.64 a	1.66 c
	50% IWR	13.87 b	51.74 c	67.69 c	65.62 c	2.07 a

Table 7. *Cont.*

Factors	Treatments		Moisture Content (%)	TSS (Brix)	Total Sugars (%)	Reducing Sugars (%)	Non-Reducing Sugars (%)
IM × IWR	CSI	100% IWR	14.77 b	51.93 e	67.12 f	65.09 g	2.03 c
		75% IWR	11.77 g	54.47 a	70.96 b	69.54 b	1.42 e
		50% IWR	13.33 e	51.95 e	68.09 e	66.08 e	2.01 c
	SDI	100% IWR	12.77 f	54.46 a	70.95 b	69.46 c	1.49 d
		75% IWR	13.33 e	51.44 f	68.09 e	66.06 ef	2.03 c
		50% IWR	13.51 d	51.06 g	66.85 g	64.76 h	2.10 b
	SSDI	100% IWR	17.13 a	52.36 c	68.38 c	66.17 d	2.21 a
		75% IWR	13.55 c	54.14 b	71.85 a	70.33 a	1.52 d
		50% IWR	14.76 b	52.20 d	68.12 d	66.01 f	2.11 b

Within each factor (IM and IWR) and their interaction (IM × IWR), means with the same letter are not significantly different at $p \leq 0.05$.

4. Conclusions

In arid and drought-prone regions, water is becoming increasingly limited. Water utilization for crop production in water-scarce areas necessitates innovative and sustainable research. In recent years, and still today, efforts to design innovative irrigation systems that save significant amounts of water and use it efficiently have been key research fields. For date palm cultivation in dry regions, the SSDI system used in this study is simple, cost-effective, and practical. The modern SSDI system was compared with the traditional CSI and SDI systems. It was found that the SSDI system can be used in water-scarce regions as it conserves water and contributes well to yield and fruit quality attributes. Although the maximum yield was obtained when 100% irrigation water was used in the SSDI system, other treatment combinations, such as SDI at 100% IWR, SSDI at 75% IWR, and CSI at 100% IWR, responded similarly and produced satisfactory results, according to the findings of this study. Similarly, the SSDI system with 50% IWR had the highest irrigation water productivity, followed by the SSDI with 75% IWR and 100% IWR. The SSDI system's fruit quality features were also positive, with a 75% IWR. Due to its positive impact on water productivity, yield, and fruit quality without changing soil chemical qualities, the SSDI method at 75% IWR appears to be the best choice for date palm irrigation in arid regions. It makes a significant contribution to reducing water resource depletion in arid environments while ensuring sufficient tree growth and productivity. Based on the present study results, the SSDI system might be highly recommended for date palm production in arid and semi-arid areas due to its high-water management efficiency in these environments.

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