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Effects of Irrigation Regimes on Khalas Date Palm Yield Under Surface and Enhanced Subsurface Irrigation Systems with Smart Control Application

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Abstract

The date palm *Phoenix dactylifera* L. is an essential desert food crop. A study was conducted for two years to determine Khalas palm variety yield response to different irrigation regimes. Bubbler system (BS) and enhanced subsurface stonewool drip system (ESDS) were tested in the Kingdom of Bahrain during the period of 2021–2023. A split-plot design was used with BS and ESDS as main plots. Irrigation regimes of 20, 30, and 50% (D2–D3) as subplots compared with crop water requirements (D1) based on Penman Monteith FAO method (PMFM). A smart volume-based control system was used in the 2nd year. The results revealed no significant differences in date yield, average weight of bunches, and soft fruits (Rutab) percent between the BS and ESDS systems ($p > 0.05$). No significant yield differences were obtained between the irrigation regimes at $p > 0.05$. Water productivity was highly significant ($p = 0.0003$ and 0.0001) regarding irrigation regimes for the two years, respectively. Compared to 1st year, the 2nd year yield has improved by 78.5 and 53.5% under ESDS and BS systems, respectively. Apart from seasonal palm yield variations, smart application has the most impact on yield improvement. It is concluded that published palm K_C coefficients may overestimate water requirements by about 50%. More water saving can be attained using smart volume-control application under BS or ESDS systems. It is vital to develop local crop coefficients for date palms under desert and humid climatic conditions similar to Bahrain.

Keywords: water requirements; desert climate; IoT; stonewool; subsurface drip; date quality

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1. Introduction

Date fruit represents the top gross production commodity in the UAE, Kuwait, and Qatar and ranked second in the Kingdom of Saudi Arabia, Sultanate of Oman, and Kingdom of Bahrain [1]. The palm tree is generally adapted to a desert climate and high soil and water salinities. Millions of date palm trees are actively growing in the Arabian Peninsula, demanding a tremendous amount of irrigation water. Apart from its small size, the Kingdom of Bahrain was historically known as the land of a million palm trees. Such an amount of irrigation water when visualized within the actual farmer practices, anticipating

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overirrigation, can be realized knowing that the number of total date palm trees in the Gulf Cooperation Countries is about 82 million [1]. Irrigation water has been applied through various flooding systems or through pressurized bubbler/drip systems. Although several studies reported the superiority of subsurface drip systems over surface drip systems, subsurface systems are still not realized at the commercial level, e.g., [2–6]. This may be attributed to the cost of installation and maintenance in addition to worries about drippers clotting due to high salt content in soil and water. On the other hand, water requirements and water use of date palm trees have been in the focus of research in the Middle East and North African region. The studies revealed that tremendous variation in water needs exist depending on climatic conditions, soil, irrigation method, water quality, and studied varieties. For example, the average daily water use per tree for 7 regions in Saudi Arabia was about 184 L, while the net annual water use ranged between 59 and 80 m^3/tree [7]. The actual measured evapotranspiration rate of Khalas trees using drainage lysimeters was reported between 2.5 and 14.6 mm/d in Kuwait [8]. Another study conducted in the United Arab Emirates estimated actual evapotranspiration of a date palm tree as 150 L/day during summer peak and 50 L/day during the mid-winter season [9]. Another study performed for four years at the International Center for Biosaline Agriculture found that peak summer water use of a palm tree varied between 190 and 130 L/day, corresponding to salinity levels of 5 and 15 dS/m, respectively [10], which is similar to the reduced water use pattern due to salinity reported by [11]. In the Kingdom of Bahrain, ref. [12] indicated that for optimum date palm yield, a yearly total of about 50 m^3/tree is required. As water scarcity is aggravated by climate change and competition from other sectors, water-saving techniques continued to play crucial role for the demanding date palm sector. On the other hand, ref. [13] reported that the research results indicated successful application of deficit irrigation practices that improved water productivity without causing significant yield reductions. Despite high humidity, Bahrain climate is characterized by high aridity with erratic seasonal rainfall of about 75 mm occurring during winter months. Thus, rain contribution to irrigation requirements is lacking when most needed during the long hot summer season. On the other hand, the effects of an innovative enhanced stonewool subsurface drip irrigation system have not been widely tested on commercial date palm fields regarding the nature of light soils that lead to tremendous loss of irrigation water and/or energy consumption for reduced duration time of irrigation and increased frequency to satisfy water needs. Moreover, irrigation of date palm trees even under drip or bubbler systems, apart from the wasteful flood system, does not depend on scientifically calculated requirements, which opens the door wide for over irrigation, especially tertiary-treated wastewater is provided free of charge. The objective of this study is focused on studying the effects of an enhanced subsurface drip system compared with a conventional well-managed bubbler system under different irrigation regimes to realize the potential of irrigation water savings without jeopardizing yield and fruit quality. In addition, smart IoT volume-based irrigation control was also tested to add to the precision of irrigation water management that may lead to savings during the second year.

2. Experimental Site and Background

A date palm database was successfully established in the Kingdom of Bahrain by the National Space Science Agency (NSSA). A joint project was undertaken by collaborative efforts between NSSA, Smart Farm Sensing (SFS) of the Netherlands, Bahrain Ministry of Municipalities Affairs and Agriculture (MMAA), and the Arabian Gulf University (AGU). The objective was initially thought to use smart technology to detect and protect palm trees from the red palm weevil and to improve and save irrigation water using stonewool with a subsurface drip irrigation system as a new innovative solution to mitigate deep drainage and enhance soil water storage capability. The suggested project was coordinated and financed by the Bahrain National Initiative for Agricultural Development (NIAD). AGU, as the principal investigator, designed and executed an irrigation regime experiment to explore water-saving potential against modeled crop water requirements with incremental reductions of 20, 30, and 50% and at the same time compare improved subsurface drip irrigation system with the bubbler system. MMAA provided a date palm farm site with a total area of 5.62 ha and 720 date palm trees of about 10 years old, including 22 varieties dominated by the Khalas variety. The trees were spaced 8 by 8 m and irrigated by an old deteriorating drip irrigation system. Figure 1 shows a remote sensing image provided by the NSSA revealing the farm and the area selected for the experiment. The PMFM method [14] was used to estimate crop water requirements using published crop coefficients and Bahrain daily weather data for the past 10 years. The irrigation regime experiment was successfully executed during the first year (2021–2022) and extended for a second year (2022–2023) to confirm the results of the first year and to explore additional benefits that may arise by introducing smart volume-based irrigation control system under the same experimental setup and design and irrigation regimes.

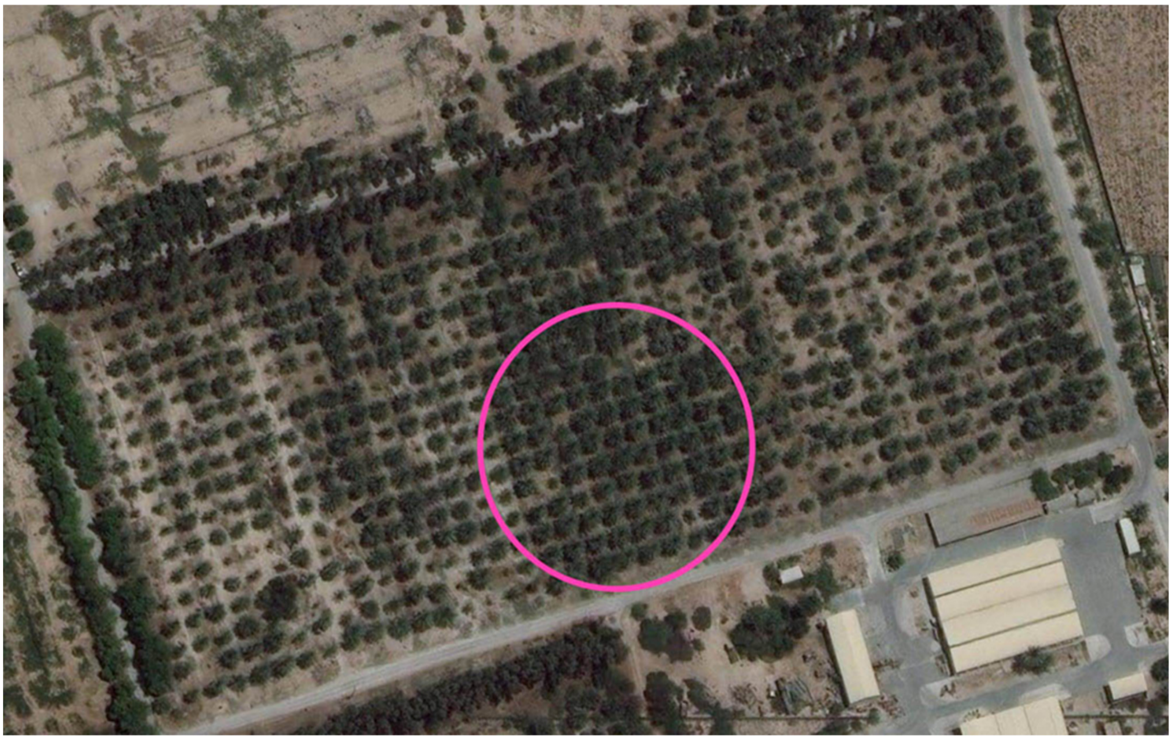

Figure 1. A remote sensing image provided by the NSSA showing an aerial view of the farm. The circle represents the area selected for the irrigation regime experiment.

3. Materials and Methods

3.1. Experimental Design

In this field experiment, only Khalas variety was selected for its popularity and importance in the Arabian Peninsula in addition to its availability in large numbers compared with other varieties in the farm. The experiment was laid out in a split-plot design with two main plot treatments and four subplot treatments. Each subplot treatment is represented by three trees as replications. Therefore, 24 total Khalas trees were selected. The selected trees were healthy and morphologically homogenous, having the same age and canopy shape with no suckers or offshoots. Trees that did not satisfy such description were excluded from the experiment.

The two main plot treatments were composed of surface bubbler and subsurface stonewool drip system. Four irrigation regimes represented the subplots vis a vis the calculated crop water requirements based on PMFM (D1) and three regimes of 20, 30, and 50% (D2, D3, and D4, respectively) of the calculated water requirements. At harvest, each tree was harvested separately, the number of bunches per tree were calculated, and the Rutab and Tamr were separated and weighed using a sensitive digital ICT equipment to the nearest gram inside the field. The statistical program JMB was used to analyze the collected data. The data collected included total yield (kg/tree), kg/bunch, Rutab percent at harvest, applied irrigation water and water productivity, and quality traits. Means separation was carried out using least square method at $p < 5\%$ level of significance. Expected results included main plot effects (irrigation system), subplot effects (irrigation regimes), and interactions between irrigation system and irrigation regimes for all the collected data. Quality traits were measured on separate Rutab and Tamr samples taken from each tree. Tertiary treated sewage effluent (TSE) water was supplied to the experiment through a newly installed 3-inch PVC pipe. The average pH and EC of the irrigation water were about 7.1 and 2.1 dS/m, respectively. Each main plot treatment received water from a 2000 L capacity tank, which was continuously fed via a float valve by the newly installed 3-inch PVC line. Each tank was equipped with a 2-horsepower irrigation pump to deliver water through a 2-inch main line to the subplot treatments integrated with the irrigation stations and solenoid valves. Each 2-inch main line was fitted with a pressure gauge before feeding the 4 solenoid valves of the subplot treatments that were coupled with 4 flowmeters and 4 pressure regulators via a 1-inch sub-main PVC pipes. The irrigation water was controlled by a calibrated time-based wired irrigation station during the first year. During the second year, the wired stations were replaced by IoT smart solar-charged controllers wired directly to the solenoid and flowmeter and connected wirelessly with the gateway. The modification was carried out with only replacing the solenoid valves with 9-volts triggering mechanism instead of the 24-volts to suit the IoT solar charged irrigation controllers, while the flowmeters were replaced with similar mechanical flowmeters provided with IoT pulsator to measure applied water. Those changes were carried out at the valve boxes without any disturbances to the main and sub-main lines. The irrigation pumps were connected to the system via IoT plugs. Figure 2 shows a schematic layout of the design without smart control, which only involved adding smart solar-charged controller beside the previously installed control boxes. Figure 3 shows and example of one replication of bubbler and stonewool systems. Each irrigation pump feeding the main plot was provided with an external bypass loop to control main line pressure and an internal loop that permits water circulation within a 130 L-drum for fertilizer mixing and application. Figure 4 shows a schematic diagram of the fertilizer application design.

3.2. Materials and Equipment

Each tree in the bubbler main plot side was fitted with one bubbler capable of delivering 0–22 L/m. Each tree in the subsurface stonewool main plot side was fitted with two stonewool blocks, each having 120 × 20 × 20 cm dimensions placed 1.5 m away from tree trunk buried at 50 cm depth and placed perpendicular to the subline feeding them through a 13 mm drip line. Each stonewool block is wrapped in water-permeable synthetic cloth with the opposite side facing away from the tree trunk blocked by a waterproof thin cardboard film to allow water to flow towards the tree roots. Each rockwool block was fed by 8 drippers (24 L/h each). One randomly selected palm tree from each subplot irrigation regime treatment was fitted with a data logger type ZL6 UMTS 3G GSM Cellular (Meter Group, Pullman, WA, USA) having a capacity to support 6 sensors with solar-charging capability and rechargeable batteries. Each of the selected trees was equipped with 3 soil moisture sensors type Teros12 to monitor soil moisture at 30, 60 and 120 cm depth. The moisture sensors were installed via an augured holes in the required depth using a locally designed device at mid-point between the trunk and the stonewool and at about 1.5 m from the trunk near the bubbler.

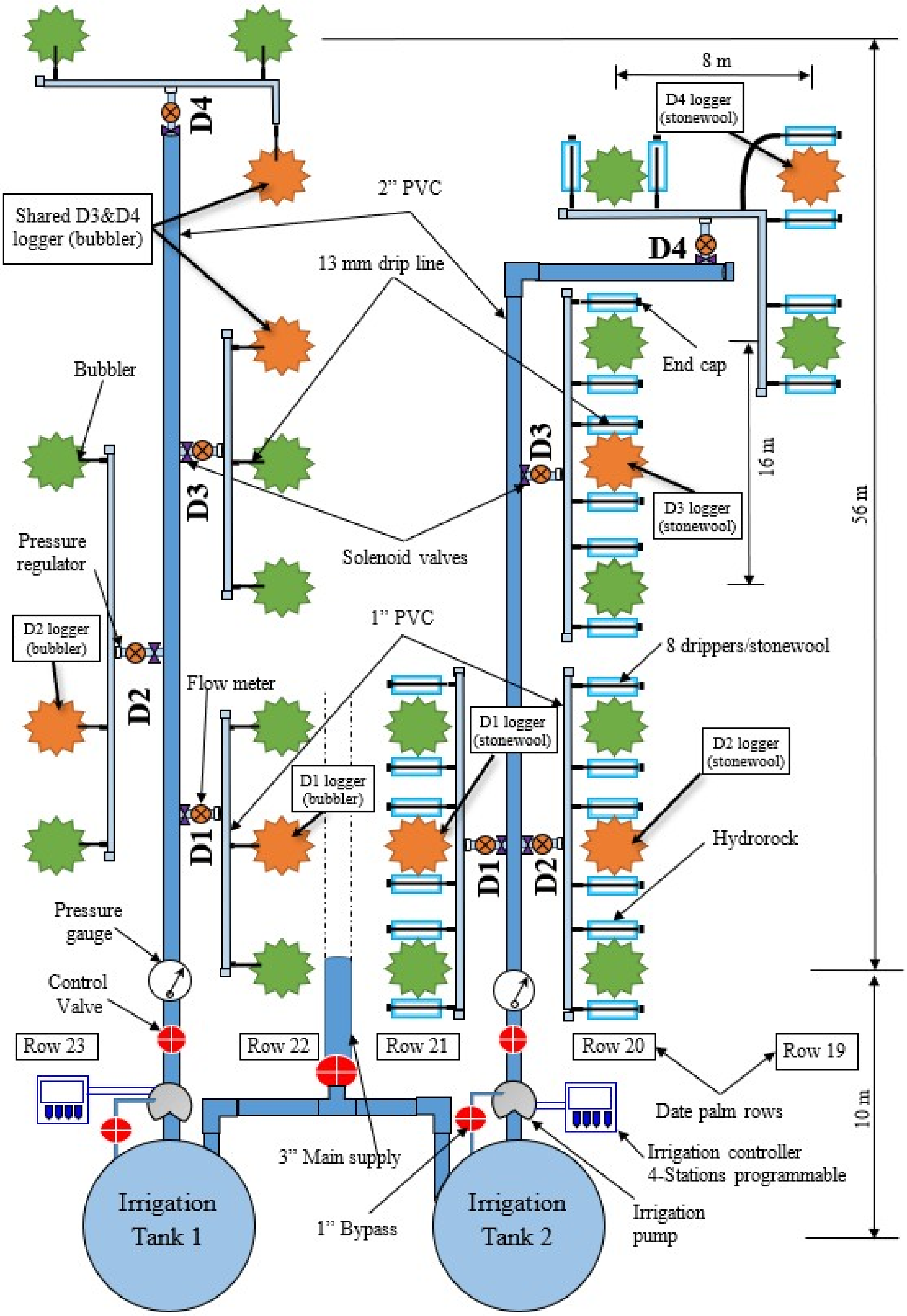

Figure 2. A schematic diagram showing the experimental design. Orange stars represent trees equipped with moisture sensors; D1–D4 represent irrigation regime treatments, including solenoid valves, flowmeters, and pressure regulators. Note that trees were depicted according to their original rows, as in the field shown in Figure 1 (empty space means excluded variety).

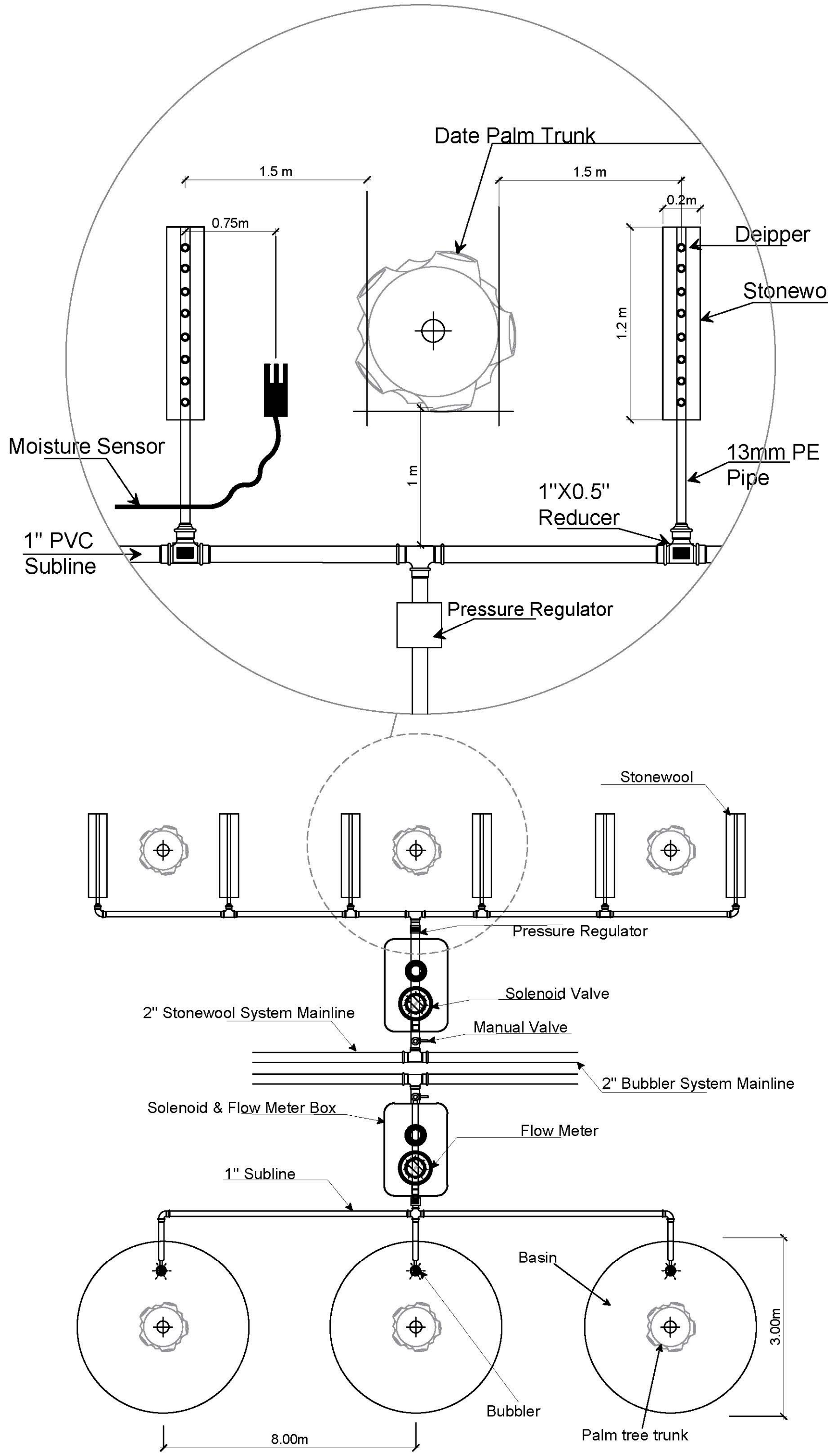

Figure 3. A diagram showing one replication of the bubbler and stonewool systems. Note that in the 2nd year, smart IoT controllers were placed beside the solenoid and flow meter boxes without disturbing any other system layout or replications (Drawing not to scale).

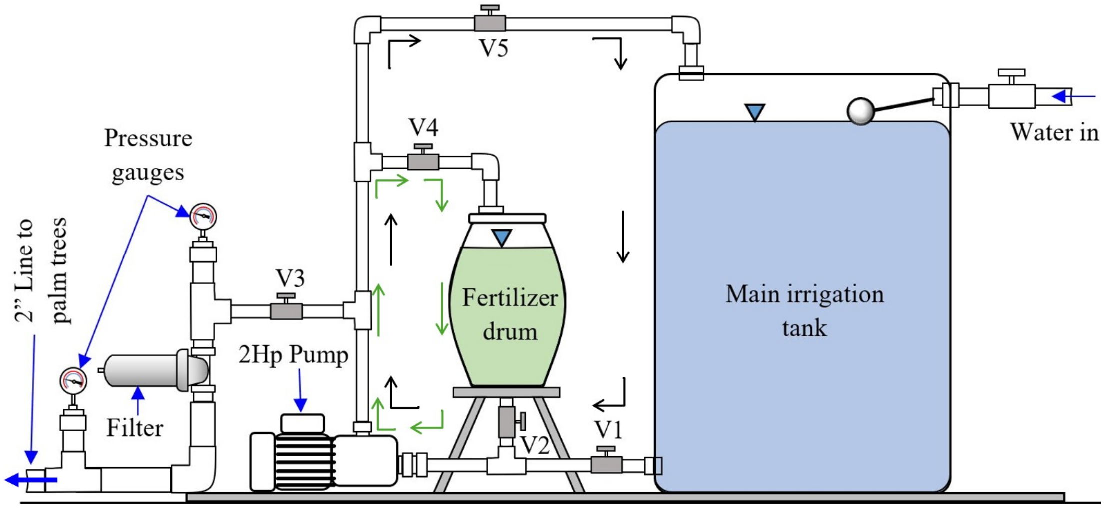

Figure 4. A schematic diagram showing the fertilizer loop application procedure: Water enters the fertilizer drum by gravity via valves V1 and V2. Then, V1 is closed after the drum is filled. Fertilizer is added to the drum, and V3 and V5 are closed while the pump is manually started for 5–10 min to dissolve and mix fertilizer (green arrows). Then, V3 is opened to apply fertilizer while V4 is adjusted to keep pressure within 2 bars. After fertilizer is applied, V2 and V4 are closed, and V1 is opened while adjusting V5 to keep pressure within 2 bars (black arrows); irrigation is completed normally from the main tank.

A Kerlink Wirnet iStation 868MHz (Thorigne Fouillard, France), outdoor LoRa with 4G gateway, was mounted on a metal pipe at 2 m height and connected with SFS AgrIoT data cloud via paid SIM card. The gateway provided soil moisture data every 5 min during the 1st season and every 30 min during the second season. The data can be accessed from AgrIoT site via a username and password using a mobile or any computer connected to the internet. The data can be accessed almost in real time depending on internet speed. During the last 8 months of the experiment, all the previous flowmeters and solenoid valves were replaced by wireless IoT smart flowmeters equipped with pulse readers and 9-volt solar-charged LoRa irrigation controllers Model UC511-D1-868M, Milesight IoT Co., Ltd., Xiamen, Fujian, China. Two LoRa Milesight portable sockets Model W5523-868M type G-UK were used to control the 2 irrigation pumps via IoT irrigation application program. Thus, the wired solenoid valves and the irrigation stations were not needed, as the control of the irrigation volume, time, and interval became possible from mobile phone or any computer connected to the internet. Soil moisture data can be retrieved on mobile in graphical and numerical formats at any time, providing information on soil volumetric water contents for each indicator tree per irrigation system and irrigation regime treatment.

3.3. Cultural Practices

Nitrogen, phosphorous, and potassium were added in the form of NPK (20:20:20) and KNO_3 (13:0:46) in the first season and NPK (15:30:15) in the second season. To apply the same amount of nutrient irrespective of irrigation treatment, the drums' internal loop was used to mix about 1 to 2 kg of fertilizer during scheduled irrigation applications provided that its minimum water volume did not exceed the drum maximum capacity (about 40 L/tree). This was accomplished, as explained in Figure 4, by manually controlling the valves feeding the internal loop and the trees while keeping the pressure at 2 bars through the internal drums' bypass loop. The total amount of added nutrients was about 460, 330, and 1.120 g/tree of nitrogen, phosphorous, and potassium, respectively, using NPK and KNO_3 between April and June 2022. Only 250, 500, and 250 g/tree of NPK were applied in February and March 2023 after flowering and pollination. The normal cultural practices include "Tarwees", which means removal of thorns, old fibers from leaf base, and old dried fronds usually carried out in January–February, followed by "Tanbeet", which means pollination of female flowers using male pollens, usually practiced during the period of February–March. This was followed by "Tahdeer or Taqwees", meaning bending and tying of fruit bundles to fronds, usually carried out 2 months after pollination. Tahdeer may be accompanied by "Al-Khaf", which is thinning of the number of bundles per tree as well as number of fruits per bundle, usually carried out in April–May. All these operations were documented by mobile camera, iPhone 11 pro and used as an archive for knowledge transfer training purposes.

Harvesting was carried out between 29 August and 1 September 2022 and between 20 and 23 August 2023 in the first and second years, respectively. The bundles were cut and counted for each tree, and the fruits were removed from the bundles and sorted as "Rutab", representing yellowish full-sized fruits, and "Tamr", representing completely soft and dark-brown-colored fruits. Rutab and Tamr of each bundle and tree were weighed using electronic WSM1 way scale (ICT International, Armidale, Australia) of 60 kg capacity ±0.5 g at the site. About 1 kg fruit samples were taken in separate packages and stored in a refrigerator for quality analysis. Part of the quality analysis was performed at the Faculty of Science, University of Bahrain.

3.4. Calculation of Crop Water Requirements

Crop water requirement was calculated on daily basis as the product of reference crop evapotranspiration ET_0 and crop coefficient Kc. ET_0 was calculated using PMFM method according to [14]. Published date palm crop coefficients (Kc) developed under desert climatic conditions in KSA were used according to [15]. ET_0 was calculated using actual Bahrain daily weather data obtained by an automatic weather station located at about 6 km from the experiment site for 10 years between 2012 and 2021. The irrigation efficiency was assumed to be 90%, as it involved drip and bubbler systems. The salt leaching requirement was taken as 10% based on FAO leaching requirement (Equation (1)), which can be written as

$$LR = \frac{EC_{iw}}{5(EC_e) - EC_{iw}} \tag{1}$$

where LR is leaching requirement, EC_{iw} is the salinity of irrigation water (2.1 dS/m for the used TSE water), and EC_e is the recommended tolerable soil paste extract salinity by date palm trees, which is assumed to be 4.6 dS/m in this experiment according to [16].

The effective evapotranspiration radius of the tree is calculated as 2.2 m, thus giving an effective evapotranspiration area of 15.21 m^2. The used K_C was 0.85 in January, 1.26 in February, 0.92 from March to June, 0.80 from July to October, and 0.65 from November to December. Gross crop water requirements of date palm (GCWR) in liters per day were calculated using the daily 10-year average ET_0, the effective tree evapotranspiration area (ETA) in m^2, the corresponding Kc, the salt leaching requirement (LR), and the irrigation efficiency (IE), as shown in Equation (2).

$$\text{GCWR (l/d)} = \frac{ET_0 \times K_C \times ETA}{(1 - LR) \times IE} \tag{2}$$

Equation (2) was used to calculate the crop water requirements on daily basis and compared with weekly and fortnightly averages. Since the differences between the daily, weekly, and fortnightly basis were found to be negligible, the fortnightly schedule was adopted as a rule for the irrigation schedule modification, i.e., the required irrigation volume will be modified every two weeks by manually adjusting the application time using the automatic irrigation station panel to cater for the gradual change in daily weather

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conditions. The fortnightly gross irrigation requirements were calculated for the whole year, representing the full irrigation crop water requirement (D1). The calculated crop water requirements were then truncated by 20, 30, and 50% to produce the three irrigation regime treatments. Table 1 depicts all the parameters used in the calculation of crop water requirements. We preferred to use the published measured crop coefficients (K_C) carried out in KSA under similar desert climatic conditions [15]. Those K_c coefficients were selected, as they were based on actual field measurement and reported to save about 12% of irrigation water compared with FAO palm coefficients. All other parameters were either measured or estimated from the experimental site. This was deemed scientifically suitable approach to answer the question of how close crop water requirement model relates to local conditions under small islands, such as Bahrain, when reduced by up to 50%. Local irrigation system depends mainly on flooding or basin systems that tends to overirrigate by many folds. We used fortnightly averages of reference crop evapotranspiration derived from 10-year hourly weather parameters obtained from automatic yearly-calibrated weather station 7 km away from the experiment site between 2012 and 2021. Most of the published irrigation and deficit irrigation studies on date palm trees used the same approach of incrementally increasing or decreasing the estimated crop water requirements based on FAO widely used PMFM. Furthermore, one recent study used a single average K_c coefficient (0.90) to calculate Khalas palm crop water requirements, which was then truncated by 25 and 50% as different irrigation water regimes [17].

Table 1. Parameters used for the calculation of crop water requirements.

Month	ETo (mm/d)	Kc	Required (Liter/Tree)
January	2.31	0.85	1123
February	2.91	1.26	1860
March	3.69	0.92	2022
April	4.65	0.92	2425
May	5.66	0.92	3033
June	6.40	0.92	3249
July	6.07	0.65	2856
August	5.35	0.65	2491
September	4.53	0.65	2034
October	3.50	0.65	1313
November	2.60	0.65	966
December	2.25	0.65	882
Irrigation efficiency (%)			0.90
Leaching requirements (%)			10
Effective tree radius (m)			2.2

The generated time–volume regression equations were used in Excel to transfer the calculated daily irrigation volumes to time of application, which were introduced into the irrigation station program and updated every two weeks.

3.5. Calibration of Irrigation Water Applications

Since the irrigation water is controlled by irrigation stations and solenoid valves, the relationship between time of application and volume must be established for each of the 8 solenoid valves representing each of the 4 irrigation regime treatments at the bubbler and stonewool subsurface systems. For each 3 replicated trees, the bubblers or the 8-dripper lines supplying the stonewool blocks were placed in separate large plastic bags to collect the applied water after 5, 10, and 20 min. The collected volume was measured using a measuring cylinder. Regression equations relating time to volume were derived for all the irrigation treatments. The regression equations were then employed using Excel program to transfer the daily required volumes to time of application that was updated every two weeks with new values and fed to the irrigation station program. This was carried out for the first year until the smart system was installed in the second year.

3.6. Application of Smart IoT Irrigation Control System

Although soil moisture sensors were excellent indicators of irrigation events, it did not provide needed information on the volume of water passing through the solenoid valve. Relying on daily readings of the 8 flowmeters before and after each irrigation was cumbersome and inconvenient. Although the system was based on application time, variation on pressure setup during fertilizer application may interrupt the applied volume. Since the irrigation water at the stonewool sides was stored and slowly released by the stonewool, soil moisture sensors response did not provide clear indication of irrigation events. Therefore, the available gateway was employed to shift the system from time-based irrigation stations to volume-based smart IoT control. Eight controllers were obtained from SFS and connected with each flowmeter and solenoid valve using the same control box of each irrigation system and regime. In addition, two smart plugs were used to link the two pumps with the smart system. The smart system was tested and started operation on first of May 2023 with complete data cloud internet programing option that was based on volume as priority followed by time of application as a precaution to avoid overirrigation in case of volume detection failure. The AgrIoT developed program provided user-friendly and flexible irrigation programing capabilities with feedback on pump operation, power consumption, irrigation start and end times and applied volumes, and graphical and tabulated soil profile moisture data in addition to warning messages on missing or incomplete irrigation events. Most importantly, solenoid valve leaks (if any) were also reported on almost real-time basis in addition to under- or overirrigations. The program also provided local weather data including forecasts to skip irrigation during rain events.

3.7. Soil Chemical and Physical Properties

A soil profile was established in the field between two trees in the center of the experiment on 20 September before the start of the experiment. Soil cores were taken at 20, 40, 60, and 100 cm depth for the determination of field bulk density and texture. Soil salinity and pH were determined in the laboratory using paste extract on samples taken from each depth. Pressure plate apparatus was used to determine field capacity, permanent wilting point, and available water. Field capacity was taken at 0.33 bar, which is suitable for light-textured soils and permanent wilting point at 15 bars. The pF curve was plotted using the best fitting equation utilizing pressure and moisture data of 0.1, 0.3, 3, and 5 bars. Moisture content at 15 bar was calculated by interpolation using the best-fitting equation. Soil element composition was determined by microwave digestion and ICP method at the Arabian Gulf University laboratory. It is worth mentioning here that no shallow water table was observed inside the 1.2 m soil profile; thus, the contribution of additional moisture by capillary rise was omitted from the calculation of irrigation water productivity.

3.8. Date Fruit Quality Determination

Date palm fruit can be divided into 5 distinctive stages based on physical appearance and chemical composition; 1—Hababouk (Habamboo or Hababoo) indicates small spherical-shaped small green fruits formed after pollination up to 5 weeks and gradually changing into oval shape. 2—Kimiri (Jimri) represents green hard stage not suitable for eating with the longest development period that lasts from berry-sized to almost oval-shaped fruits (9 to 14 weeks). 3—Khalal (Besser or Balah) shows the actual color of the variety (greenish yellow, yellow, pink, or red), taking 3 to 5 weeks, and the fruits are mature and edible. Some varieties are mainly consumed at Khalal stage. 4—Rutab is characterized by softening and changing color at the tip into brown or black depending on variety with increased rate of total sugars, decreasing rate of active acidity, moisture, and tannin contents. 5—Tamr indicates the final completely ripe fruits with maximum total sugars and lower moisture contents (<25%) with suitable condition for storage. As the harvesting process involved direct sorting of fruits and taking samples for quality analysis at the edible stages of Khalas (Khalal, Rutab, and Tamr), Khalal and Rutab were directly separated in the field for weighing and named "Rutab" for the sake of analysis, while the completely transformed soft dark-colored fruits were weighed separately and named Tamr in the analysis.

During the first-year, brix reading was carried out by soaking 9 g of Tamr samples in 45 mL distilled water and using Reichert® Digital Handheld refractometer (Depew, NY, USA) after one hour without filtration. In the second year, water content (WC %), vitamin C content (VCC %), total soluble sugars (TSS), and total titratable acidity (TTA %) were determined for Tamr and Rutab by a collaborating team from University of Bahrain. Water content, TSS, and TTA were determined according to [18]. Vitamin C content was determined using standard ascorbic acid, deionized water, filter paper funnel, and 100 mL flasks in addition to UV/Vis spectrophotometer and cuvette tubes.

4. Results and Discussion

4.1. Soil Properties and Calibration of Irrigation Water Application

Table 2 depicts the main physical and chemical soil properties obtained from the soil profile. The bulk density was low for mineral soils. However, studies of the soil bulk density under trees reported bulk densities as low as 0.92 g/cm^3 [19]. In addition, another report stated a soil bulk density of Bahrain between 0.82 and 1.61 g/cm^3 [20]. Furthermore, it has been reported that most cultivated soils of Bahrain have horizons that contain fine-grained gypsum crystals with a very low bulk density [21]. It is also worth mentioning that the samples were taken from 10-year active date palm root zone that usually extends to more than one meter. Therefore, such samples are expected to contain roots that, upon drying, reduce soil weight relative to the constant core volume. Reports by [20] indicated that Bahrain's soil field capacity ranges between 5 and 60% and 1 and 30% at the permanent wilting point. Soil salinity was very high at medium soil depths. This could be due to irregular irrigation. However, SAR is low, meaning no infiltration hazards for the bubbler irrigation system [16]. Table 3 shows soil element concentrations in the tested soil samples compared with some standard indicators according to [22,23].

Table 2. Soil chemical and physical properties obtained from site soil profile.

Depth (cm)	pH	EC$_e$ (dS/m)	BD (g/cm^3)	Moisture at FC (%Vol)	Moisture at PWP (%Vol)	TAM (mm/m)	OM (%)	SAR	% Sand	% Silt	% Clay	Soil Texture
20	7.86	8.92	1.12	46.72	23.68	46.07	0.41	0.39	54.40	36.00	9.60	Sandy loam
40	7.84	20.87	0.73	32.37	16.04	32.66	0.76	3.11	52.40	38.00	9.60	Sandy loam/Loam
60	7.82	18.67	0.75	48.02	26.57	42.88	0.76	2.93	26.40	38.00	35.60	Clay loam
80	7.83	14.72	0.78	26.79	6.60	40.38	0.62	1.42	42.40	38.00	19.60	Loam
100	7.89	7.84	0.98	33.96	9.53	48.86	0.48	0.72	38.40	40.00	21.60	Loam

BD; dry bulk density, FC; field capacity, PWP; permanent wilting point, TAM; total available moisture, OM; organic matter, SAR; Sodium adsorption ratio. pH and EC$_e$ based on soil paste extract.

Table 3. Element concentration (mg/L) in the tested soil samples compared with certain standards (mg/kg).

Element	Soil Sample Depth (cm)					EU Permissible Limits [22]	Typical Range [23]
	20	40	60	80	100		
K	125.9	1098.6	1147.9	681.2	366.6	NA	NA
Fe	391.3	3146.7	3424.4	2081.8	1627.9	NA	200–500,000
Ca	75,633.3	89,585.9	96,617.3	184,288.6	204,525.6	NA	NA
Mn	28.6	226.9	223.8	93.5	103.9	NA	7–10,000
Na	412.0	4340.6	4122.8	2339.4	1220.1	NA	NA
Mg	5683.8	35,568.8	32,793.0	13,825.6	8791.4	NA	NA
Cu	20.2	24.8	24.4	14.8	12.4	140	2–250
Zn	3.4	18.6	15.1	8.9	5.6	300	1–900
Ni	14.8	14.9	11.7	9.2	4.5	75	3–1000
Cr	20.2	24.8	24.4	14.8	12.4	140	2–250
Cd	0.2	0.2	0.0	0.6	0.4	3	NA
Pb	1.4	4.8	0.0	0.0	0.3	300	NA

NA; Not available.

Table 4 shows the main results of the irrigation water calibration that aimed at determining the relationships between the duration of irrigation in minutes (m) and the delivered volume (liters/tree).

Table 4. The results of irrigation regime calibration for the determination of the relationship between the irrigation duration (min) and applied volume (liters).

Irrigation System	Irrigation Regime	Duration (min)	Volume (Liters)	Regression Equation	R^2
Bubbler	D1	5 10 20	83 153 287	$y = 0.0737x - 1.1774$	0.9999
	D2	5 10 20	77 158 263	$y = 0.0813x - 1.8374$	0.9867
	D3	5 10 20	73 125 240	$y = 0.0893x - 1.378$	0.9994
	D4	5 10 20	62 134 227	$y = 0.0917x - 1.263$	0.9864
Stonewool	D1	5 10 20	47 92 195	$y = 0.1006x + 0.465$	0.9999
	D2	5 10 20	57 92 182	$y = 0.1182x - 1.3788$	0.9966
	D3	5 10 20	52 95 184	$y = 0.1134x - 0.85$	0.9999
	D4	5 10 20	50 91 189	$y = 0.1068x - 0.085$	0.998

4.2. Crop Water Requirements

The maximum calculated crop water requirement was 112 (L tree^{-1} d^{-1}), which occurred during the month of June, while the minimum was 28 L tree^{-1} d^{-1}, which occurred during December and January. It is worth mentioning here that the presented values in Table 4 represents the monthly total crop water requirements based on average biweekly values obtained from daily calculations and adopted for the application of the irrigation regimes.

4.3. Soil Moisture Analysis

Since the calculation of daily applied volume using the flowmeter readings was impractical, the soil moisture data were downloaded from AgrIoT server and monitored on daily basis before the installation of the smart IoT system. The data were used only as indicator of irrigation events. The soil moisture pattern under the bubbler system showed clear hills and valleys in response to the daily irrigation applications. On the other hand, the moisture data of the stonewool system did not show clear patterns of hills and valleys. This may be attributed to the fact that the total water applied was halved (two-side mode of application) and retained inside the stonewool for slow release to the surrounding soil. Furthermore, field observations revealed that the soil surface under the stonewool system remained dry in response to irrigation events throughout the two years, while the tree basins under the bubbler system witnessed continuous weed growth and regrowth after cutting. Using the total moisture contents under bubbler system clearly showed daily water use pattern indicated by a sharp rise due to irrigation and gradual declining rates mainly due to water use. Figure 5 shows an example of a normal daily pattern of irrigation and moisture depletion. Figure 6 shows an example of under-irrigation together with a lack of irrigation events detected on real-time moisture data that can be obtained on a mobile screen via the AgrIoT data cloud site of SMS.

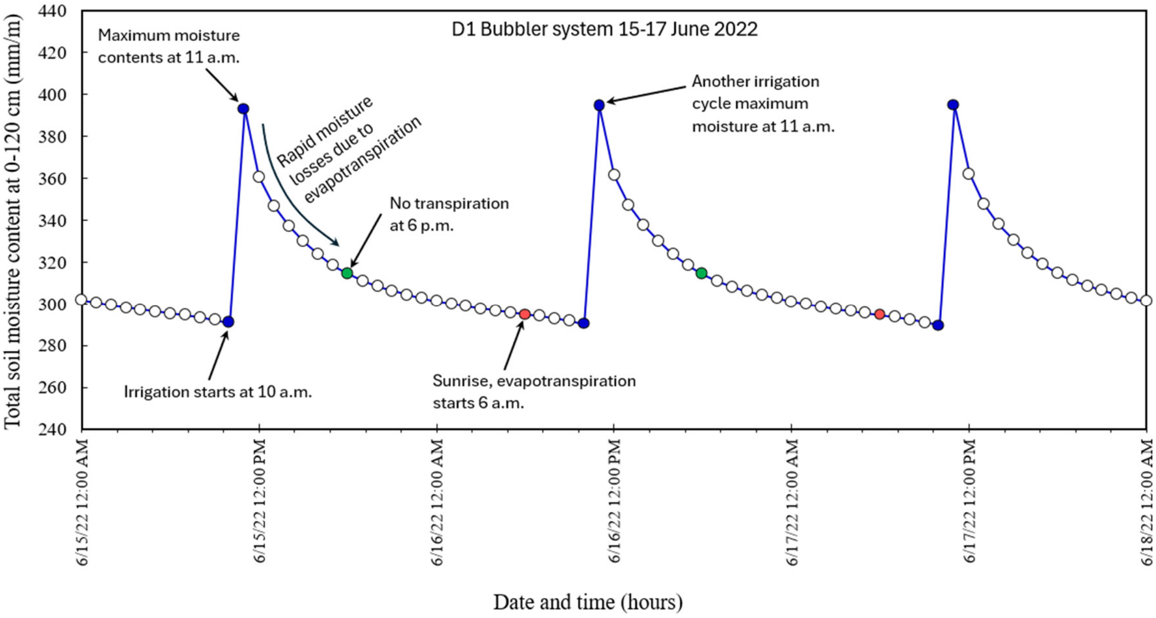

Figure 5. Example of zoomed-in moisture data showing normal 3 days repeated soil moisture patterns due to irrigation and evapotranspiration under bubbler system.

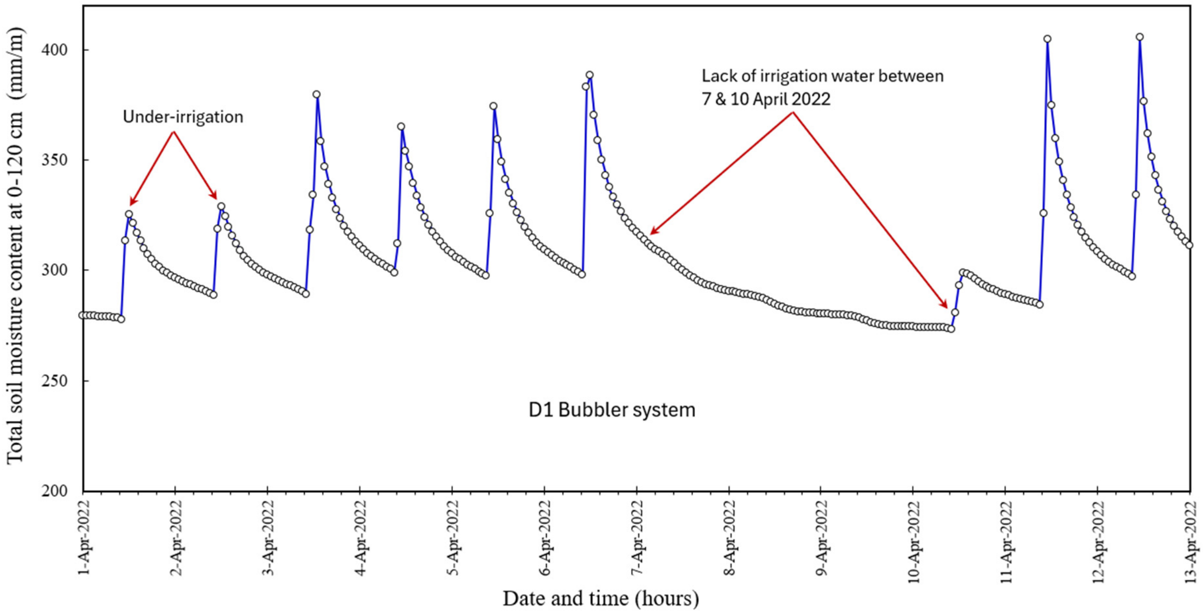

Figure 6. An example of under-irrigation events and a lack of irrigation (water supply maintenance issue) in addition to normal peaks of daily irrigations reflected on total soil profile moisture contents (mm) and obtained in almost real-time via the mobile app.

4.4. Total Applied Water

Table 5 shows the total applied water (liters/tree) using the initial flowmeter readings and the readings after harvesting between 3 January and 5 September 2022. The table also presents the calculated water requirements using the Penman–Monteith method for the same period. There was a clear variability between the required and applied water on each irrigation system. However, there were no overirrigations.

Table 5. Total required and applied water (liter/tree) using PMFM and flowmeters readings between 3 January and 5 September 2022.

Irrigation Regime	Total Required Water (Liter/Tree)	Total Applied Water (Liters/Tree)	
		Bubbler	**Stonewool**
D1	24,144	22,909	20,161
D2	19,316	18,084	16,546
D3	16,901	11,918	9017
D4	12,079	10,991	7941

D1 indicates calculated requirements, and D2–D4 indicate 20, 30 and 50% reductions.

Table 6 shows the total required and applied water volumes between 13 May and 31 December 2023 after the installation of the smart controllers. Adding up the total applied water (liters/tree) using the normal flow meter readings between 5 September 2022 and 9 April 2023 and the smart flowmeter readings between 13 May and 5 September 2023, a full-year record of applied water was obtained, except for the time used for installation of smart controllers, flowmeters, and solenoid valves.

Table 6. Total required and applied water (liter/tree) using PMFM and smart controller between 13 May and 31 December 2023.

Treatments	Total Required Water (Liter/Tree)	Total Applied Water (Liters/Tree)	
		Bubbler	Stonewool
D1	15,878	18,464	15,771
D2	12,700	11,757	11,597
D3	11,123	10,525	10,462
D4	7948	7632	7438

D1 indicates calculated requirements and D2–D4 indicate 20, 30 and 50% reductions.

Based on the general definition of efficiency, a formula was suggested and used to calculate the percentage of satisfying the required water volume per irrigation regime treatment, given by Equation (3):

$$IRSE = \frac{SAW}{SRW} \times 100 \tag{3}$$

where *IRSE* is the irrigation regime satisfaction efficiency (%) and *SAW* and *SRW* are the seasonal applied water and seasonal required water, respectively (liter/tree). The overall irrigation system satisfaction efficiency was calculated as the ratio between the sum of the seasonal applied water under bubblers or stonewool systems and the sum of the seasonal water requirements (liters/tree). Table 7 shows the irrigation satisfaction efficiencies per irrigation regime treatment and per irrigation system for one year between 5 September 2022 after the first-year harvest and 5 September 2023 after second-year harvest. The total applied water was used to calculate the water productivity, as will be explained under the yield results and analysis section. The IRSE was given to better understand the interpretation of results related to yield and date quality under the two systems.

Table 7. Irrigation regime satisfaction efficiency (IRSE) and overall irrigation system satisfaction efficiency (ISSE) as % of crop water requirement (CWR liter/tree) for one year between 5 September 2022 and 5 September 2023.

System	Regime	Normal Flowmeter [a]	Smart Flowmeter [b]	SAW (Liter/Tree)	SRW (Liter/Tree)	IRSE (%)	ISSE (%)
Bubbler	D1	15,253	13,443	28,695	24,692	116.2	98.6
	D2	12,509	7225	19,734	19,754	99.9	
	D3	5739	7913	13,651	17,284	79.0	
	D4	5868	5081	10,949	12,353	88.6	
Stonewool	D1	8853	10,425	19,278	24,692	78.1	81.7
	D2	9562	7176	16,738	19,754	84.7	
	D3	5907	8098	14,005	17,284	81.0	
	D4	5374	5118	10,491	12,353	84.9	

[a] Based on normal flow meter readings between 5 September 2022 and 9 April 2023. [b] Based on smart flowmeter data between 13 May 2023 and 5 September 2023. SAW, SRW, IRSE as defined in the text, ISSE is the irrigation system satisfaction efficiency.

After the installation of the smart system, more data on the applied irrigation volume became available on real time via mobile or through download from the AgrIoT site. It included daily applied water volumes (liters) per irrigation regime treatments at both bubbler and stonewool sides; daily time duration of applications (minutes); daily leaked volume (if any); and warning messages in case of under-irrigations, a lack of irrigation events, and over-irrigations in addition to the required irrigation for each irrigation regime.

4.5. First-Year Yield Analysis

4.5.1. Date Palm Yield (First-Year)

The actual harvested number of bunches per tree varied due to pollination failure and/or damage during the practice of bunch pending and thinning. However, in the first season the maximum and minimum harvested bunches per tree were 11 and 3, respectively. The highest yield per tree was obtained under the highest water application D1 bubbler with 66.7 kg. While the lowest yield per tree was obtained under D3 bubbler treatment with 17.4 kg. The statistical analysis of the date yield showed no significant differences between the yield of the two irrigation systems (44.2 and 42.8 kg/tree for the bubbler and stonewool systems, respectively). Similarly, there were no significant differences in yield regarding the irrigation regime treatments. Figure 7 shows the average date yield of the irrigation regime treatments (kg/tree). The analysis of the average weight of bunches per tree showed no significant differences between the two irrigation systems (6.2 and 5.6 kg/bunch for stonewool and bubbler systems, respectively).

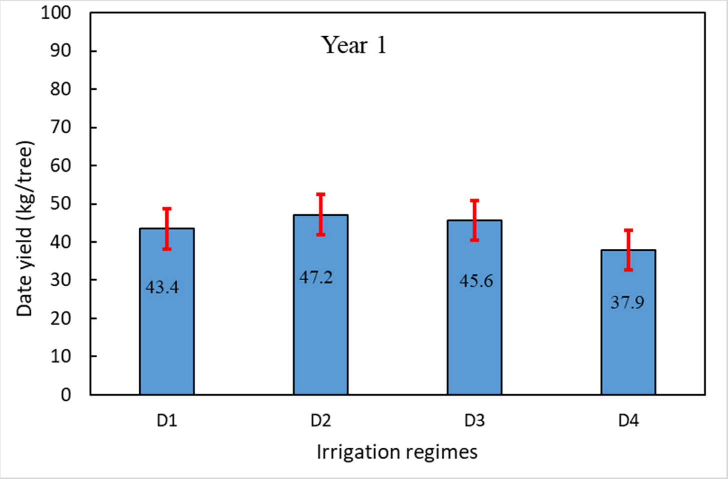

Figure 7. First-year average date yields (kg/tree) per irrigation regime; red lines indicate standard error (±5.2).

4.5.2. Water Productivity (First-Year)

The term water productivity used in this research study is defined as the harvested commercial yield (kg) divided by the seasonal total applied irrigation water (m^3). The total applied irrigation water was calculated from the actual flowmeter readings between 3 January (start of monitoring) and 5 September 2022 (just after first-year harvest). The statistical analysis revealed no significant differences in water productivity between the stonewool and bubbler systems. However, the stonewool system resulted in higher water productivity (3.5 kg/m^3) compared with 3.0 kg/m^3 for the bubbler system. This may be compared with the presented figures by [2], who reported 1.59 kg/m^3 for subsurface drip irrigation knowing that our figures were based on the calculated applied water for 8 months. It is logical to assume that the difference between stonewool and bubbler system was due to reduced surface evaporation since the water was directly applied at the root zone under the stonewool system compared with the surface application of the bubbler system. However, field observations clearly indicated quick water infiltration under the bubbler system owing to the nature of the soil texture at the site, although losses due to soil surface evaporation and continuous weed growth cannot be omitted. Furthermore, losses due to deep drainage cannot be omitted at the bubbler system, while the stonewool has better holding capacity that may have led to more moisture retention at the root zone. One drawback faced during the experiment was the ability to detect missing irrigation using the data of soil moisture sensors placed in the center of a 1.5 m distance between the stonewool and tree trunk. This could be attributed to the ability of stonewool storage and the slow release of moisture of half of the applied water pertaining to two sides of stonewool application/tree compared with high response of sensors at the single bubbler/tree system. This could be solved by placing soil moisture sensors immediately beside the stonewall side facing the tree while the deeper sensor (100 cm depth) could be placed below the stonewool to detect deep percolation (if any). On the other hand, regarding water productivity, the irrigation regime treatments have shown highly significant differences ($p = 0.0003$). Both the 30 and 50% irrigation regime treatments have resulted in significantly higher water productivity (4.4 and 4.1 kg/m^3), respectively, compared with 2.7 and 2.0 kg/m^3 for 20% and no reduction treatments, respectively. Figure 8 shows the water productivity of the first year.

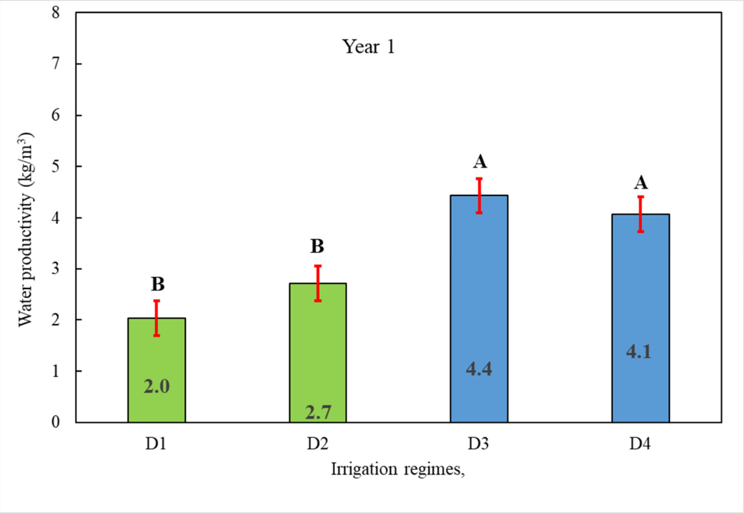

Figure 8. The first-year water productivity (kg/m^3) of irrigation regime treatments. Means followed by the same letters are not significantly different at the 5% level according to least square means separation. Lines indicate standard error (±0.337 SE).

4.5.3. Date Fruit Quality

The statistical analysis of the total dissolved sugars, as indicated by brix reading, did not show significant differences between the irrigation systems (33.9 and 31.8% for bubbler and stonewool, respectively). No significant differences were obtained regarding the irrigation regime treatments; however, the brix values showed an ascending order between 31.1% under required water treatment and 34.3% under the 50% regime. This may be attributed to the moisture content of the fruits pertaining to the irrigation regime treatments but did not reach significant differences.

4.6. Second-Year Yield Analysis

4.6.1. Date Palm Yield (Second-Year)

The maximum and minimum harvested bunches per tree were 11 and 5, respectively. The highest single tree yield was obtained under the 20% regime (D2 stonewool) with 113.8 kg, while the lowest tree yield was obtained under the same first-year 30% regime (D3 bubbler) treatment with 36.5 kg. The statistical analysis of the date palm yield showed no significant differences between the yield of the two irrigation systems (67.8 and 76.4 kg/tree for the bubbler and stonewool systems, respectively). Similarly, there were no significant differences in yield regarding the different irrigation regimes. Figure 9 shows the average date palm yield of the irrigation regime treatments (kg/tree) obtained in the second year. The date palm yield was highly improved through consistent and better monitoring and application of irrigation water during the second year as a result of smart control application. The analysis of the average bunch weight did not reveal significant differences between the two irrigation systems; however, as in the first year, the stonewool obtained the highest bunch weight per tree (9.4 kg), while the bubbler system resulted in 8.3 kg.

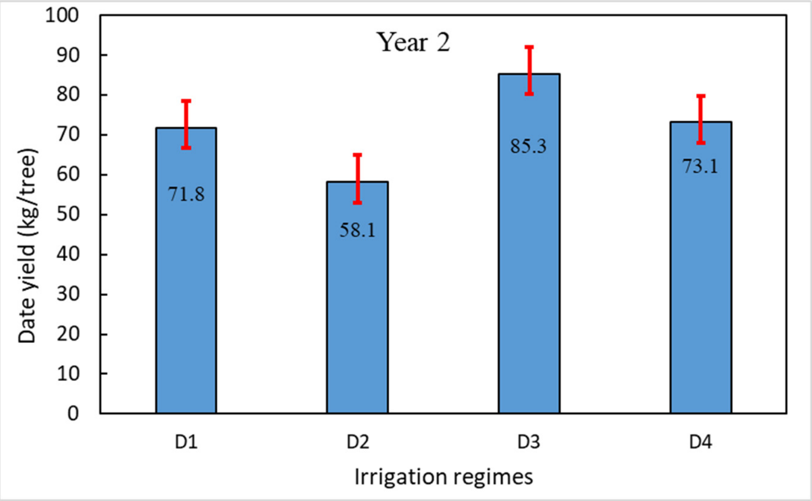

Figure 9. Second-year average date yields (kg/tree) per irrigation regime; red lines indicate standard error (±7.5 for D1 and ±6.7 for D2–D4).

The analysis of irrigation regime treatment effects on bunch weight revealed significant differences at $p = 0.022$. It is hard to explain that the 50% regime and no-reduction regime (D1) treatments have resulted in significantly higher bunch weights (10.3 and 9.4 kg, respectively) compared with the 20% regime (6.7 kg). In addition, both the 30% and 20% regimes have statistically similar bunch weights apart from the judgment of the expert palm service man who performed the pruning, bending, and tying of bunches after pollination.

It is worth mentioning here that one tree of the D1 regime under the bubbler system lost most of the yield due to rodent attack and was treated as a missing subplot. Rodents were controlled, and no further attacks were observed. The analysis of the Rutab percentage did not show significant differences between the irrigation systems and between the different irrigation regime treatments. However, the percentage of Rutab under the stonewool system recorded 23.3% compared with 16.5% under the bubbler system, confirming the first-year results. The lowest Rutab percentage was obtained as in the first year under the 50% irrigation regime treatment (13.5%), and the highest Rutab percentage was obtained under the D1 irrigation regime treatment (24.7%). The results obtained support the supposition that irrigation quantity may impact the date ripening process by affecting the physiochemical processes of date fruit phase transformation and ripening. However, under the current design, this did not produce significant differences. This could be attributed to known date palm seasonal yield variations.

4.6.2. Water Productivity (Second-Year)

The applied water after the first-year harvest was calculated using the normal flowmeter readings between 5 September 2022 and 9 April 2023 when the installation of the smart flowmeters and smart controllers started. Then, the actual applied volumes were obtained using the newly installed controllers and smart flowmeters for the period 13 May 2023 up to the end of the experiment on 31 December 2023. The two volumes were added to form a complete one-year record between 5 September 2022 and 5 September 2023 except for the period between 10 April and 12 May 2023, as explained before. Table 8 shows the combined water volume calculation for one year obtained just after the first-year harvest on 5 September 2022 and up to 5 September 2023 after the second-year harvest.

Table 8. Calculated applied irrigation water (liter/tree) using normal and smart flowmeters during the 2nd year between 5 September 2022 and 5 September 2023 for the stonewool (stw) and bubbler (bub) systems.

Irrigation Treatment	Applied Water Using Normal Flowmeters (Liter/Tree) [1]	Applied Water Using Smart Controllers (Liter/Tree) [2]	Total Applied Water (Liter/Tree)
D1 stw	8853	10,425	19,278
D2 stw	9562	7176	16,738
D3 stw	5907	8098	14,005
D4 stw	5374	5118	10,491
D1 bub	15,253	13,443	28,695
D2 bub	12,509	7225	19,734
D3 bub	5739	7913	13,652
D4 bub	5868	5081	10,949

[1] Normal flow meter readings between 5 September 2022 and 9 April 2023. [2] Smart controller readings between 13 May 2023 and 5 September 2023. D1–D4 as explained before.

As in the first year, the irrigation systems did not show significant date yield differences. However, the stonewool system has resulted in higher water productivity compared with the bubbler system (5.3 and 4.4 kg/m^3, respectively). On the other hand, the regime treatments have resulted in highly significant differences in water productivity at $p < 0.0001$. Figure 10 shows the result of water productivity (kg/m^3) for the irrigation regime treatments. As expected, the 50 and 30% regimes have resulted in the highest water productivity compared with the full regime and 20% regime, confirming the first-year results.

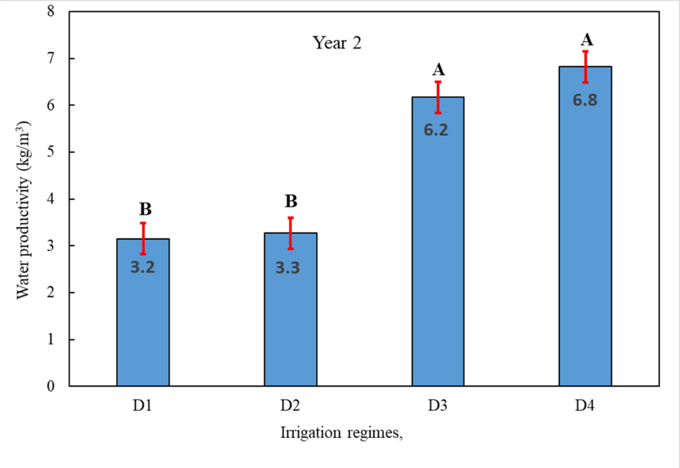

Figure 10. The second-year water productivity (kg/m^3) of the irrigation regime treatments. Means followed by the same letters are not significantly different at the 5% level. Vertical lines represent the standard error (±0.442).

4.6.3. Second-Year Date Quality Analysis Results

According to date fruit quality indices, the higher the total soluble sugars (TSS), pH, and vitamin C (VC) were, the better the quality was. Conversely, the lower the titratable acidity (TTA) was, the better the quality (taste) was. It is known through the maturation process that Rutab has higher levels of water content (WC) and TTA compared with the Tamr stage, which usually has higher pH, TSS, and VC and lower WC. Tables 9 and 10 show the obtained quality analysis data for Rutab and Tamr. Table 11 shows a summary of the quality indices' statistical analysis regarding the irrigation systems (stonewool and bubbler). As shown in Table 10, the statistical analysis confirmed the first-year results of no significant differences between the two irrigation systems on TSS contents for both Rutab and Tamr fruit stages. However, the irrigation system has resulted in significantly lower TTA in both Rutab and Tamr stages, with 0.054 and 0.072% for the stonewool and bubbler systems, respectively, at the Rutab stage, while the Tamr stage recorded 0.036 and 0.043% for the stonewool and bubbler systems, respectively. Moreover, the stonewool system has resulted in significantly higher pH only at the Rutab stage (5.92) compared with 5.17 for the bubbler system. There were no significant differences between the two irrigation systems regarding pH at the Tamr stage and vitamin C and water contents at both tested fruit stages.

Regarding the irrigation regime treatments effect, significant differences were obtained only at the Rutab stage with respect to pH, where the 20% regime has resulted in the highest pH value (6.0) compared with full regime (5.5) and 30% regime (5.1) treatments. The 50% regime treatment has resulted in pH 5.7. No significant interactions between the irrigation system and irrigation regime treatments were found in all the tested parameters except for TTA under the Tamr stage at $p = 0.013$, as shown in Figure 11.

Table 9. The results of the quality index analysis for Rutab samples in the second year. D1–D4 indicates the irrigation regime treatments under the stonewool (stw) and bubbler (bub) systems.

Treatment	TSS	TTA (%)	pH	VC (%)	WC (%)
D1 stw	17.1	0.058	5.37	0.028	59
D1 stw	15.0	0.045	6.26	0.039	57
D1 stw	19.0	0.054	5.75	0.028	64
D1 bub	NA	NA	NA	NA	NA
D1 bub	14.9	0.067	4.71	0.026	62
D1 bub	17.7	0.051	5.52	0.024	68
D2 stw	13.2	0.050	6.09	0.017	67
D2 stw	22.8	0.032	6.70	0.027	55
D2 stw	21.6	0.048	5.83	0.023	63
D2 bub	23.8	0.064	5.65	0.024	75
D2 bub	26.9	0.067	6.09	0.023	63
D2 bub	13.1	0.058	5.58	0.029	55
D3 stw	16.2	0.067	5.21	0.023	69
D3 stw	19.8	0.054	5.46	0.034	63
D3 stw	21.3	0.058	5.63	0.031	69
D3 bub	12.7	0.059	4.74	0.035	62
D3 bub	19.2	0.058	4.94	0.028	71
D3 bub	22.1	0.093	4.50	0.040	66
D4 stw	16.9	0.070	5.69	0.019	61
D4 stw	20.8	0.058	6.50	0.034	65
D4 stw	21.1	0.058	6.51	0.032	64
D4 bub	13.9	0.058	5.48	0.027	68
D4 bub	11.4	0.093	5.16	0.026	75
D4 bub	17.7	0.147	4.60	0.031	72
Maximum	26.9	0.147	6.7	0.040	74.9
Minimum	11.4	0.032	4.5	0.017	54.6

Table 10. The results of the quality index analysis for the Tamr samples in the second year. D1–D4 indicates the irrigation regime treatments under the stonewool (stw) and bubbler (bub) systems.

Treatment	TSS	TTA (%)	pH	VC (%)	WC (%)
D1 stw	56.2	0.032	6.03	0.035	8
D1 stw	51.8	0.038	5.40	0.072	19
D1 stw	71.5	0.040	6.03	0.065	8
D1 bub	NA	NA	NA	NA	NA
D1 bub	56	0.042	6.43	0.063	14
D1 bub	56.7	0.054	5.54	0.055	10
D2 stw	53.5	0.050	5.84	0.050	14
D2 stw	49.5	0.026	6.55	0.048	16
D2 stw	50.8	0.038	6.29	0.120	10
D2 bub	55.4	0.035	6.24	0.044	14
D2 bub	57	0.032	6.35	0.059	16
D2 bub	51.6	0.042	6.25	0.069	15
D3 stw	51.6	0.050	6.07	0.047	11
D3 stw	52.0	0.040	6.35	0.106	12
D3 stw	53.6	0.035	6.24	0.083	13
D3 bub	56.5	0.034	6.04	0.056	12
D3 bub	50.1	0.034	6.32	0.053	17
D3 bub	54.6	0.043	5.99	0.051	11
D4 stw	46.2	0.030	6.14	0.035	14
D4 stw	49.2	0.030	6.31	0.058	20
D4 stw	48.1	0.034	5.63	0.027	9
D4 bub	52.8	0.053	6.09	0.048	15
D4 bub	54.6	0.051	6.23	0.054	11
D4 bub	56.2	0.053	5.92	0.069	12
Maximum	71.5	0.054	6.6	0.120	20.2
Minimum	46.2	0.026	5.4	0.027	7.9

TSS: total soluble sugars, TTA: total titratable acids, VC: vitamin C content, WC: water content. NA: Not available, fruit lost to rodents at Hababouk stage.

Table 11. Statistical analysis results of irrigation system effects on Rutab and Tamr quality indices.

Index	Rutab			Tamr		
	Status	Stonewool	Bubbler	Status	Stonewool	Bubbler
TSS (%)	NS	18.7	17.5	NS	52.8	54.8
TTA (%)	$p = 0.037$	0.054 B	0.072 A	$p = 0.036$	0.036 B	0.043 A
VC (%)	NS	0.028	0.028	NS	0.062	0.057
pH	$p = 0.0004$	5.92 A	5.17 B	NS	6.07	6.12
WC (%)	NS	63.0	66.8	NS	13.0	13.4

TSS: total soluble sugar. TTA: total titratable acidity. VC: vitamin content. WC: water content. NS: not significant. Means in the same row followed by different letters are significantly different at 5%.

In a similar study carried out in the Sultanate of Oman involving subsurface drip irrigation at 60, 40, and 20% of water requirements compared with bubbler system, they found that the subsurface drip system has higher water use efficiency at all the tested irrigation regimes compared with the bubbler system [6]. Another similar study conducted in Al-Ahsa, Saudi Arabia, with Khalas palm trees indicated higher water productivity of the subsurface drip system over the surface drip system and controlled bubbler surface irrigation system [16]. However, both studies did not include stonewool blocks as a mitigating soil storage facility against deep drainage, although this study did not reveal significant differences in date yield between the enhanced subsurface (stonewool) and bubbler irrigation systems. However, the stonewool system during the second year had higher yields than the bubbler system except at the 50% regime. This may be attributed to the fact that at the 50% irrigation regime level, the trees will be subjected to some water stress as most of the applied water may remain inside the stonewool blocks.

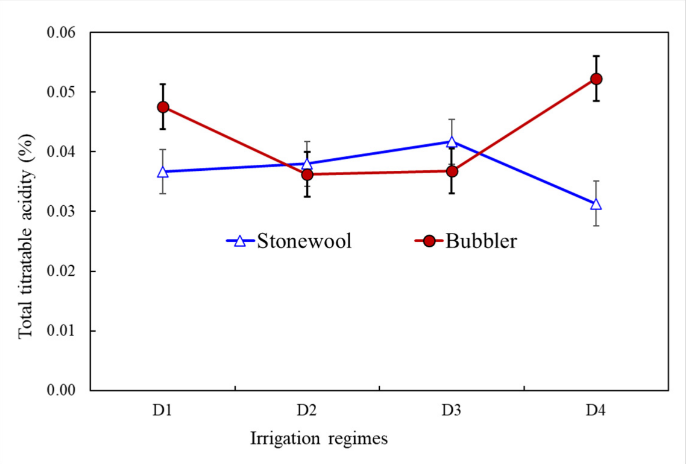

Figure 11. Interaction between irrigation system and irrigation regime treatments for total titratable acidity (TTA %) at the Tamr stage. Vertical lines indicate standard error (±0.004).

Taking into consideration the reported seasonal 50 m^3/tree suggested for Bahrain, our modelled seasonal crop water requirements (24.6 m^3/tree) together with regimes of 20, 30, and 50% of the modeled would annually save about 25.4, 30.3, 32.8, and 37.7 m^3/tree, respectively. However, farmer practices were reported to over-irrigate beyond these levels mainly due to traditional flood irrigation system. Assuming tree spacing of 8 by 8 m resulting in about 156 trees/ha, our modeled calculated water needs would save about 4000 m^3/ha, while the modest 30% regime treatment would save about 5117 m^3/ha. This is supported by the results of the study of [5] under similar environmental conditions of Al-Ahsa in Saudi Arabia that indicated annual water application amounts of 21.04, 22.76, and 58.71 m^3/tree for automated control subsurface sensor-based, automated control subsurface time-based, and traditional surface irrigation systems, respectively.

4.7. Conclusions

The volume-based smart irrigation system ensured precise water application and tremendously improved yields at both stonewool subsurface and bubbler systems by about 78.5 and 53.5%, respectively, during the second year with average improvement by about 44.7%. Although other environmental factors may have contributed to such improvements, including seasonal known yield variation, the effects of precise water application fostered by smart irrigation application during the second year have made great contribution. This supposition was supported by direct field observations and careful professional date palm services practiced during close supervision of two years.

The following conclusions can be drawn from this study:

1. Based on local Bahrain average daily weather conditions, the 10% leaching factor, and the published KSA date palm crop coefficients, the daily calculated Khalas water needs ranged between a maximum of 112 L $tree^{-1}$ d^{-1} during June and a minimum of 27 L $tree^{-1}$ d^{-1} during December. A reduction of the above calculated water requirements by up to 50% did not result in significant yield losses in two years of experimentation. This is about 50.8% savings without reduced irrigation regime treatments. More savings are expected using up to 50% reduction in the Kingdom of Bahrain since farmers' practices tend to apply many folds of the calculated water requirements.

2. Care should be taken before generalizing those results, as long-term experiment of about 4–5 years must be executed to confirm that such water consumption can be sustained against both yield quantity and quality.
3. Using a stonewool subsurface irrigation system did not result in a significant increase in Khalas date yields compared with a properly managed bubbler irrigation system. However, care should be taken when using an irrigational bubbler system without careful consideration of timing, duration, water quality, and soil moisture indicators.
4. The stonewool subsurface system could prolong the period of Khalas Rutab availability compared with the bubbler irrigation system. However, such results need more studies.
5. Stonewool subsurface system has improved the quality of the harvested Rutab and Tamr in terms of total titratable acidity and pH, while the total soluble solids, vitamin C, and water content of Rutab and Tamr were not significantly affected.
6. The utilization of smart irrigation technology greatly enhanced water application precision and provided a smart and efficient method of irrigation system monitoring and evaluation. It reduced water losses through real-time leakage detection and overirrigation as well as eliminated missing irrigations provided that proper soil moisture indicator sensors were installed and integrated into the smart IoT system.

4.8. Recommendations

1. The determination of date palm crop coefficients under the prevailing climatic and soil conditions should be carried out for a proper estimation of crop water requirements in the Kingdom of Bahrain and similar countries with similar climatic and soil conditions.
2. Research-based proper irrigation regime strategy can be adopted to optimize water utilization in the date palm production sector without jeopardizing quality and productivity with great water savings, especially in areas suffering from water scarcity.
3. Applied research for testing and optimization of large-scale smart irrigation technologies should be encouraged for greater water savings potential and robust control, monitoring, and evaluation over conventional irrigation techniques.
4. The stonewool system with synthetic cloth wrapping provided excellent options for deep drainage mitigation, dripper clotting, and cutback in soil evaporation and weed growth. However, economic viability and durability should be investigated and weighed against an array of benefits/drawbacks of weed control, intercropping, and soil surface evaporation.

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References

1. FAO. *Value Chain Study: Date Palm in the Arab Region*; FAO: Rome, Italy, 2023.
2. Al-Amoud, A. Date Palm Response to Subsurface Drip Irrigation. In *CSBE/SCGAB Annual Conference 2006*; Paper No. 06-204; The Canadian Society for Bioengineering: Edmonton, AB, Canada, 2006.
3. Al-Amoud, A. Subsurface Drip Irrigation for Date Palm Trees to Conserve Water. *Acta Hortic.* **2010**, *882*, 103–114. [CrossRef]
4. Dewidar, A.; Al-Fuhaid, Y.; Al-Hilal, S.; ben Saleh, M. Water saving in Arid region: A comparison of surface and subsurface drip irrigation systems for irrigation of date palms. *Am. J. Innov. Res. Appl. Sci.* **2016**, *2*, 289–296.
5. Mohammed, M.; Riad, K.; Alqahtani, N. Efficient IoT-Based Control for a Smart Subsurface Irrigation System to Enhance Irrigation Management of Date Palm. *Sensors* **2021**, *21*, 3942. [CrossRef] [PubMed]
6. Dhehibi, B.; Ben Salah, M.; Frija, A.; Aw-Hassan, A.; Al Wahaibi, H.; Al Raisi, Y.; Dewidar, A.Z.; Al Fuhaid, Y.; Nejatian, A.; Niane, A.A. Economic and environmental evaluation of different irrigation systems for date palm production in the GCC countries: The case of Oman and Saudi Arabia. *Desalination Water Treat.* **2022**, *263*, 116–124. [CrossRef]
7. Alamoud, A.I.; Fawzi, S.M.; Saad, A.A.H.; Ahmed, M.A. Reference evapotranspiration and date palm water use in the kingdom of Saudi Arabia. *Int. Res. J. Agric. Sci. Soil Sci.* **2012**, *2*, 55–169.
8. Bhat, N.; Lekha, V.; Suleiman, M.; Thomas, B.; Ali, S.; George, P.; Al-Mulla, L. Estimation of water requirements for young date palms under Arid climatic conditions of Kuwait. *World J. Agric. Sci.* **2012**, *8*, 448–452.
9. Alyamani, W.; Green, S.; McCann, I.; Clothier, B.; Abdelfattah, M.; Pangilinan, R. Water use of date palms in the saline desert soils of the United Arab Emirates. In *XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014): International Symposium on Tropical Fruits*; Mitra, S., Nissen, R., Eds.; ISHS: Leuven, Belgium; pp. 67–74. [CrossRef]
10. Al-Muaini, A.; Green, S.; Dakheel, A.; Abdullah, A.H.; Abou Dahr, W.A.; Dixon, S.; Kemp, P.; Clothier, B. Irrigation management with saline groundwater of a date palm cultivar in the hyper-arid United Arab Emirates. *Agric. Water Manag.* **2019**, *211*, 123–131. [CrossRef]
11. Abdelhadi, A.; Salih, A.; Sultan, K.; Alsafi, A.; Tashtoush, F. Actual Water Use of Young Date Palm Trees as Affected by Aminolevulinic Acid Application and Different Irrigation Water Salinities. *Irrig. Drain.* **2020**, *69*, 427–440. [CrossRef]
12. Almansoori, T.A.; Al-Khalifa, M.A.; Mohamed, A.M.A. Date Palm Status and Perspective in Bahrain. In *Date Palm Genetic Resources and Utilization*; Al-Khayri, J., Jain, S., Johnson, D., Eds.; Springer: Dordrecht, The Netherlands, 2015. [CrossRef]
13. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
14. Allen, R.; Pereira, L.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements—Fao Irrigation and Drainage Paper No. 56*; FAO: Rome, Italy, 1998.
15. Al-Quraishi, A.; Ismail, S.; Awad, M. Effects of water regimes and palm coefficient on growth parameters, date yield and irrigation water use of tissue culture-regenerated “Barhee” date palms grown in a newly established orchard. *Irrig. Drain.* **2016**, *65*, 491–501. [CrossRef]
16. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture. Irrigation and Drainage Paper # 29*; FAO: Rome, Italy, 1985. Available online: https://www.fao.org/4/t0234e/t0234e00.htm (accessed on 7 December 2025).
17. Alnaim, M.S.; Mohamed, M.S.; Mohammed, M.; Munir, M. Effects of Automated Irrigation Systems and Water Regimes on Soil Properties, Water Productivity, Yield and Fruit Quality of Date Palm. *Agriculture* **2022**, *12*, 343. [CrossRef]
18. Ibrahim, M.A.; Hamzah, H.A. Effect of the harvest date, storage period and package on storability of date palm (*Phoenix dactylifera* L. CV. Taberzal) fruits. *Plant Arch.* **2019**, *19*, 226–231.
19. Sadeq, M.A.; Abido, M.S.; Salih, A.A.; Alkhuzai, J.A. The Effects of Mesquite (*Prosopis juliflora*) on Soils and Plant Communities in the Deserted Rangelands of Bahrain. *Int. J. For. Res.* **2020**, *2020*, 8810765. [CrossRef]
20. Al-Shabaani, A.H. *Status of the Agricultural Land, Soil and Ground Water in Bahrain*; Agricultural Engineering and Water Resources, Agriculture and Marine Resources, Ministry of Municipality and Urban Planning: Manama, Bahrain, 2014; 41p. Available online: http://www.fao.org/fileadmin/user_upload/GSP/docs/NENA2014/Bahrein.pdf (accessed on 7 December 2025).

21. Bridges, E.M.; Burnham, C.P. Soils of the State of Bahrain. *J. Soil Sci.* **1980**, *31*, 689–707. [CrossRef]
22. Srivastava, V.; Sarkar, A.; Singh, S.; Singh, P.; de Araujo, A.; Singh, R. Agroecological responses of heavy metal pollution with special emphasis on soil health and plant performances. *Front. Environ. Sci.* **2017**, *5*, 64. [CrossRef]
23. Hooda, P. (Ed.) *Trace Elements in Soils*; Wiley: Hoboken, NJ, USA, 2010.