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*Full Length Article*

# Smart Monitoring, Sap-Flow, Stem-Psychrometer and Soil-Moisture Measurements Tools for Precision Irrigation and Water Saving of Date Palm

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## Abstract

Wireless real-time monitoring with sensor technologies is an important component of intelligent systems for precise and sustainable crop water management. However, this approach has never been investigated on date palm trees in arid environments using standard Aflaj and bubbler irrigation systems. The goal of this study was to perform smart monitoring of temperature (T), solar radiation ($R_s$), relative humidity (RH) and wind speed ($u$), as well as sap flow (SF) rates and stem water potential (SWP) in addition to soil volumetric water contents (VWC). The findings revealed that climatic variables had greatest impact on SF rates with the following order: air temperature > solar radiation > vapor pressure deficit > wind speed. Plant water stress under the Aflaj system reached up to -5.8 MPa while bubbler system kept water stress at its optimal level at an SWP of -1 MPa. Moreover, the crop evapotranspiration ($ET_c$) using a modified Penman-Monteith (PM) model found with 49 and 31% higher in both summer and winter seasons when compared to SF rates. Additionally, a regression model was developed to simulate SF using combined factors of $R_s$ and T, with $R^2 = 0.94$ for Aflaj and 0.93 for bubbler systems. When the modern/bubbler system combined with the soil-plant-atmosphere continuum tools and real-time monitoring-based irrigation was used, the optimum reductions of irrigation water use over the Aflaj system has reached 92 and 91% during summer and winter seasons, respectively. Moreover, the financial analysis showed that modern/bubbler irrigation system produced more crop yield and farm revenue. Hence, this study revealed that advance technology, instrumentation and monitoring systems have ability to explore a significant potential for measuring the combined plant factors such as plant vigor, production efficiency, nutrient-water uptake volume and timing. These systems also have the ability to track tree responses for changes in weather, water status, moisture levels, soil conditions, and water stress. © 2021 Friends Science Publishers

**Keywords:** Wireless intelligent system; Real-time monitoring; Sap flow; Stem water potential; Simulation; Water management; Water saving

## Introduction

The need to use water more efficiently has increased globally as a result of population growth, urbanization, and growing environmental awareness (Victor 2012). By 2050, the global population will have risen from current 7.7 billion to around 9.8 billion people (Boretti and Rosa 2019) and due to rising population many countries are experiencing acute water scarcity (Mancosu *et al.* 2015). According to (Lezzaik and Milewski 2018), the Middle East and North Africa (MENA) states are among the most water-scarce countries and the region's population is forecasted to double in the next 50 years causing a reduction of per capita water supply by 40%.

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Oman is a part of the MENA area with a low freshwater recharge because of less average annual rainfall of 75 to 100 mm (Al-Hatrushi 2013). The country is relying on two major water resources: surface and groundwater. Irrigation in Oman, on the other hand, is a fundamental component of the country's agricultural activities, with the agricultural sector consuming over 90% of all groundwater resources (Jabri *et al*. 2019). Farmers mostly use fresh groundwater for irrigation, which, combined with the scarcity of water, puts pressure on the groundwater aquifer and inefficient use may also contribute to water scarcity (Khatri 2019).

Irrigation water supply is a major limiting factor for agricultural crop productivity, particularly in dry regions, due to water loss and scarcity (Shen *et al.* 2013). Water loss is induced by the environment in a variety of ways, including soil evaporation, water runoff, deep percolation, and transpiration due to a high vapor pressure deficit (Zhou and Zhao 2019; García *et al.* 2020). In addition, limited rainfall, low recharge and harsh climatic conditions are all factors that contribute to a water scarcity for irrigation in arid areas (Nemera *et al.* 2020). As a result, substantial irrigation water demand, accurate transpiration and plant-soil interaction is critical for reducing water loss in a water-stressed environment (Zhao and Zhao 2015). Therefore, sensor-based plant-water relations integrated with wireless-communication are vitally needed to precisely quantify plant water requirements supported by real-time monitoring mechanisms (Im *et al.* 2018; Tiglao *et al.* 2020). The estimation of sap flow rates (SF) is a systematic plant-based monitoring approach that can quantify the plant internal osmotic movement and physiological parameters under various environmental conditions (Paul-Limoges *et al.* 2020). As a result, the SF measurements are regarded as one of the most accurate indicators of plant water and nutrient uptake (Chen *et al.* 2020). For large trunk, with dimeter greater than 25 cm, trees such as date palm, two main methods namely Thermal Dissipation Method (TDM) and Heat Ratio Method (HRM) have been investigated to estimate the SF or plant transpiration for the actual soil-plant-atmosphere continuum system (Vandegehuchte and Steppe 2013). Although both methods differ in the way of installing them into the plant, they follow same principle of how they work. They follow a heat pulse as a tracer and examine sap, nutrient, and water transport through the xylem (Merlin *et al.* 2020). These two methods have been used to quantify the SF for a variety of plants, including apple and olive (Cammalleri *et al.* 2013) and natural sugarcane cultivation (Dingre and Gorantiwar 2020). Stem water potential (SWP) sensors can also be used to determine plant water status by measuring gravitational, matric, and osmotic potentials (Spinelli *et al.* 2017). Therefore, PSY sensor was used to evaluate the fluctuations in xylem tissue, however under non-stressed conditions, the recovery from water stress can also be observed (Luo *et al.* 2016). The PSY can also be used on a variety of perennial crops, including pecan and walnut trees, as well as olive trees (Spinelli *et al.* 2018). The stomatal transpiration and actual evaporative demands can also be accessed which may also observed with the effects of stress and salinity on water productivity (Spinelli *et al.* 2016). On the other hand, monitoring volumetric soil water content (VWC), soil temperature and electrical conductivity at various soil-depths by soil moisture sensors are also important to determine the actual consumption of water from the soil and to avoid excessive water-use (Mekala and Viswanathan 2019). These sensors were employed to communicate data on the soil profile in order to establish irrigation water management and scheduling (Domínguez-Niño *et al.* 2020). These sensors can operate within threshold limits, *i.e*., field capacity (FC) and permanent wilting point (PWP) to control irrigation system and to reach up to the specified moisture levels (Tiglao *et al*. 2020).

The SF rates and vapor pressure deficit (VPD) are significantly correlated with climatic variables *i.e*., $R_s$, T, and VPD (Ma *et al.* 2017). In sunny versus monsoon conditions the SF and $R_s$ are directly proportional, illustrating the associated plant water demands (Link *et al.* 2020). Therefore, the SF and PSY combined with soil-moisture data were successfully utilized to optimize irrigation water demand under diverse environmental conditions (O'Keefe *et al.* 2020). The monitoring systems based on wireless sensor networks (WSN) can support in the development of sustainable strategies while improving the water productivity in the farming communities (Milliron *et al.* 2018). Rao *et al*. (2017) reported the deployment mechanism of WSN in a date palm plantation to establish an effective data collection.

The fruit of the date palm (*Phoenix dactylifera* L., Arecaceae) is the principal agricultural crop in the MENA region, having contributed significantly to people's health and culture for over 5000 years (Chandrasekaran and Bahkali 2013). Due to an increase in global demand, date consumption is expected to reach 13.5 million tons by 2025, reflecting the importance of date fruit in the global economy (Adroit Market Research 2019). Dates are grown on over 49% of the total agricultural area in Oman, with more than 200 types and an average irrigation water demand of 8342 $m^3$/ha/year (Al-Harrasi *et al.* 2014; Abdulrasoul *et al.* 2019). However, more than 80% of date agriculture relies on traditional flood irrigation, which can result in significant water loss and increase the risk of water scarcity (Al-Mulla and Al-Gheilani 2018). As a result, sensor-based monitoring, in conjunction with wireless sensor networks (WSN), is critical for anticipating water loss and consumption, as well as date yields.

Only a few studies have looked at the use of soil-plant atmospheric continuum WSN based linkages and environmental parameters on date palm trees. Hence, wireless based real-time monitoring using sensor technologies are an important component of intelligent systems to enable precise and sustainable crop water management. Nevertheless, this technology has never been investigated in an arid environment on date palm trees under traditional Aflaj and bubbler irrigation systems. Therefore, this study was undertaken to rigorously analyze the outcome of two date palm orchards in Oman irrigated by traditional/flood (Aflaj) and modern (bubbler type) systems by monitoring SF, VWC, PSY, soil moisture sensors and corresponding weather parameters connected with WSN. Therefore, this study's main goal was to undertake a thorough analysis of the outcome of two date palm orchards in Oman irrigated by traditional/flood (Aflaj) and modern (bubbler type) systems by smart monitoring the SF, VWC, PSY, soil moisture sensors and corresponding weather parameters connected with WSN. The study's main goal was accomplished through (a) introducing most contemporary, high-tech sensors and instrumentations for best irrigation management practices at traditional/Aflaj and modern/bubbler irrigation systems (b) investigating the applicability of smart monitoring of factors, including T, Rs, relative humidity and wind speed together with sap flow rates (SF) and SWP in addition to soil VWC in improving irrigation water saving and (c) conducting a cost/benefit analysis to evaluate water productivity of using the two different, Aflaj and bubbler, irrigation systems.

## Materials and Methods

### Study location and dataset

**Study area:** Prior to the sensors installation, two separate date palm farms were selected in Halbaan, an area located at the west side of Muscat, the capital of Sultanate of Oman (Fig. 1). One farm was irrigated by a traditional flood irrigation method locally known as the Aflaj system (Fig. 1a) and another one was irrigated by a modern bubbler system using micro irrigation equipment (Fig. 1b). The Aflaj irrigated farm was located at 23° 36' 43.25" N, 58° 1' 57.46" E while the bubbler irrigated farm was located at 23° 38' 46.06" N, 58° 2' 15.23" E. The traditional Aflaj system is an open channel irrigation system whereas the modern/bubbler irrigation, system is a widely practiced modern method for slowly providing the water and nutrients to the roots of plants, to minimize the evaporation.

### Plant selection

Both farms were cultivated with the same date palm variety *i.e.*, Naghal palm, a popular commercial variety in Oman. Hence, this variety will be referred to as a Naghal palm for the rest of the manuscript.

### Data set

In each of the two farms, the Aflaj irrigation farm (AIF) and the bubbler irrigation farm (BIF), three healthy Naghal palms of similar age (12 years) and height (11 m) were randomly selected with a trunk diameter of 68 cm. The three Naghal palms were selected as triplicate of same environment to have credible data. The study was conducted from January 2015 to December 2016.

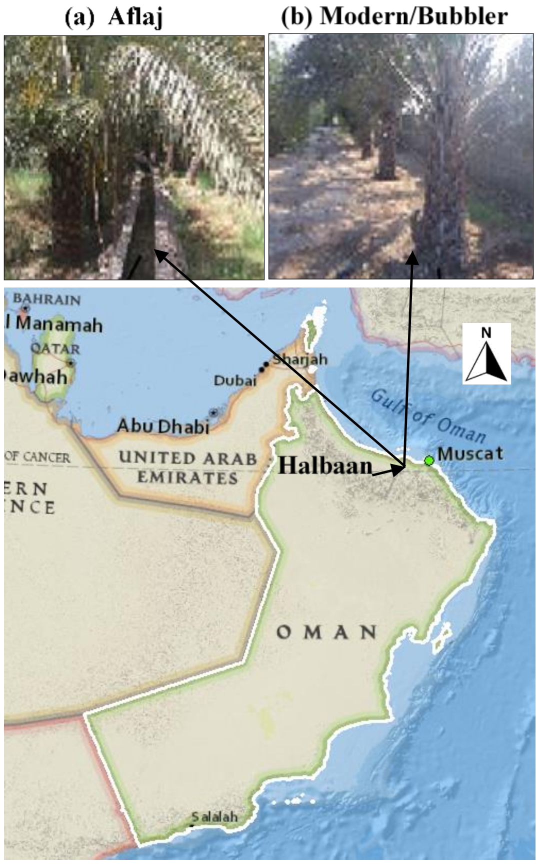

**Fig. 1:** Aflaj and modern bubbler irrigation farms. Aflaj irrigated farm located at 23° 36' 43.25" N, 58° 1' 57.46" E while the modern bubbler irrigated farm was located at 23° 38' 46.06" N, 58° 2' 15.23" E

### Soil sensors for volumetric water content monitoring

Volumetric soil water content (VWC) sensors (Model: 5TE, Meter Group, Washington, USA) were installed for each tree at three soil depths of 25, 50 and 75 cm beneath the Naghal palms for all three Naghal palms in each farm. A total of eighteen VWC sensors were thus installed in both farms. The VWC data were recorded every fifteen minutes *via* a wireless data logging system (Model: Em50, Meter Group, Washington, USA). Then, the recorded data was transferred from the data logging system *via* the internet for subsequent retrieval using ECH$_2$O Utility interface software).

### Plant based monitoring-sap flow meter and stem psychrometer

Sap flow and water potential were measured using sensors of sap flow meter (SFM) and stem psychrometer (PSY)

(Models: SFM and PSY, ICT-International, Australia), respectively. Both sensors were installed under the leaf stems of each Naghal palm. The data was recorded in the units of kg $hr^{-1}$ for SFM and MPa for PSY, respectively. The recorded data was logged, acquired and retrieved in the same process is mentioned in VWC monitoring and wireless communication system sections. Both sensors were installed for all the trees separately in AIF and BIF. These sensors were considered powerful and flexible instruments to quantify whole tree water stress.

### Meteorological data

Due to the close vicinity (15 Km) of both the farms, a fully automatic weather station (Model: ATMOS41, Meter Group, Washington, USA) was installed between both the farms to monitor weather variables. The weather station was composed of wind speed and direction sensors (Model: DS-2 sonic anemometer), high resolution dual spoon rain gauge sensor (Model: ECRN-100), air temperature and relative humidity sensor (Model: VP4-RH) and incoming solar radiation sensor (Model: LPO2 pyranometer). The wireless Em50 data logger was used to record these weather parameters every fifteen minutes.

### Crop water requirement

The crop water requirement was calculated using the following equation:

$$ETc = ETo \times Kc \tag{1}$$

Where, $ET_c$ is crop evapotranspiration [mm $d^{-1}$], $K_c$ is crop coefficient factor [dimensionless] that varies from crop to crop and according to growth stages; and based on the growth stage of the monitored Naghal palm, Kc value was used as 0.90 following Allen *et al.* (1998). $ET_o$ is reference crop evapotranspiration [mm $d^{-1}$], calculated using the modified FAO Penman-Monteith (PM) model of Allen *et al.* (1998).

$$ETo = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} U (e_s - e_a)}{\Delta + \gamma(1 + 0.34U)} \tag{2}$$

Where, $ET_o$ reference evapotranspiration [mm $day^{-1}$], $R_n$ net radiation at the crop surface [MJ $m^{-2}$ $day^{-1}$], G soil heat flux density [MJ $m^{-2}$ $day^{-1}$], T air temperature at 2 m height [°C], U wind speed at 2 m height [m $s^{-1}$], $e_s$ saturation vapor pressure [kPa], $e_a$ actual vapor pressure [kPa], $e_s$-$e_a$ saturation vapor pressure deficit [kPa], Δ slope of the vapor pressure curve [kPa $°C^{-1}$], γ the psychrometric constant [kPa $°C^{-1}$].

### Irrigation water applications

Irrigation volume was recorded as a single time amount as well as an amount applied based on weekly, monthly and seasonal irrigation at both AIF and BIF for the summer (from June to August) and winter (from November ember to February) seasons. In AIF, the irrigated water volume was calculated based on the information of applied volume.

### Vapor pressure deficit

Vapor pressure deficit (VPD) was calculated from air temperature, T and relative humidity, RH following Ficklin and Novick (2017) as a difference between actual vapor pressure, $e_a$ and saturation vapor pressure, $e_s$.

$$VPD = e_a - e_s \tag{3}$$

$$e_a = \frac{R_H}{100} \times e_s \tag{4}$$

$$e_s = 0.6108 \times \exp\frac{(17.24 \times T)}{(T + 237.3)} \tag{5}$$

### Wireless communication system

The recorded data were transferred from all sensors to their corresponding data loggers. The data were logged every fifteen minutes and transmitted from the data loggers to an internet server through the general packet radio services (GPRS) cellular telephone system. This system was based on global system for mobile (GSM) communication and existing services such as circuit-switched cellular phone connections. Therefore, real time monitoring was established for all the sensors installed in both the farms during the entire two years of the study period.

### Socio-economic analysis

A socio-economic analysis was conducted through surveys and observations for both farms. In which data were compared to analyze the costs and benefits. The analysis (Table 1) focused on the farm's cropped area, crop types, crop selling information, costs of establishment, labor expenses, farm expenditures and revenues, irrigation events and frequency and seasonal and annual profits with depreciation cost analysis to assess the real and actual socio-economic situation of the farm.

### Statistical Analysis

Pearson's correlations (Eq. 6) between SF rates (SF) and meteorological factors: $R_s$, T, VPD and U for the data points from summer and winter seasons were determined for AIF and BIF.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x}_i)^2 \sum(y_i - \bar{y}_i)^2}} \tag{6}$$

Where r = correlation coefficient, $x_i$ = values of the x-variable in a sample, x-bar = mean of the values of the x-variable, $y_i$ = values of the y-variable in a sample, y-bar = mean of the values of the y-variable. The correlation coefficient (*r*) value of $r \geq 0.7$, $0.5 < r < 0.7$ and $\leq 0.5$, denoted strong, moderate, and weak correlation, respectively. Moreover, an empirical formula was derived by regression analysis between measured and simulated sap flow rates for the Aflaj and bubbler system.

## Results

### Daily volumetric water content

Daily Volumetric soil water content (VWC) at both AIF and BIF irrigation farms for summer and winter were measured at 25, 50 and 75 cm soil depths at the location of Naghal palms. The results (Fig. 2) showed that due the increase of air temperature in summer, the number of irrigation times has increased during summer than winter in both farms. During winter, an average of three irrigation times and seven times per month for both AIF and BIF, respectively, was observed. However, the irrigation times have increased during summer to five irrigation times and eleven times in the AIF and BIF, respectively. The amounts of daily volumetric soil water content (VWC) have varied from shallow to deeper soil depths. The irrigation water accumulated in higher content at deeper soil depths. The variation in the VWC between the soil depths was observed under both irrigation systems of both farms and at both winter and summer. However, this variation between soil depths in VWC was higher under AIF than it was under BIF farm. Moreover, this variation was higher during winter than it was during summer. During summer, the difference in VWC from shallowest to deeper soil depth reached 1.0 $m^3/m^3$ in BIF and 6.3 $m^3/m^3$ in AIF farm. On other hand, during winter, difference in VWC from shallowest to deeper soil depth reached 2.5 $m^3/m^3$ in BIF and 9.5 $m^3/m^3$ in AIF farm. Furthermore, the mount of VWC supplied to the BIF farm was between 9.5 and 14.8 $m^3/m^3$ during the whole season including winter and summer, whereas it was between 13.8 and 23.1 $m^3/m^3$ for the AIF farm, indicating that AIF under Aflaj irrigation system used surplus water for irrigation as compared to the BIF.

### Sap flow *vs*. meteorological factors

The results presented in Table 3 showed a strong correlation, $R^2 = 0.85$ and 0.81, with T and very good correlation, $R^2 = 0.74$ and 0.76, was found with $R_s$ for both AIF and BIF, respectively. The VPD results also showed good influence on sap flow variations with $R^2 = 0.73$ and 0.63 for the AIF and BIF, respectively. However, the correlation with U was the lowest among the above meteorological factors with $R^2 = 0.37$ and 0.22 for the AIF and BIF, respectively.

### Water uptake and course of sap flow

During both summer and winter seasons, the water uptake inside Naghal palm started to initiate at 06:00 with sunrise and progressively increased up to around noon, then started to decrease after around 13:00–14:00 h. This parabolic shape of SF activity inside the plant corresponded directly to hourly change of temperature and solar radiation throughout the day and night (Fig. 3). Hence, the maxim water uptake took place during noon time of the day whereas the minimum water uptake took place during night time.

**Table 1:** Financial characteristics for AIF and BIF irrigated date palm trees

| | AIF | BIF |
|---|---|---|
| Costs (USD) | | |
| Establishment Cost (fixed) | 5200.0 | 16900.0 |
| Cost for manures | 44.9 | 44.9 |
| Cost of trees related work | 6319.4 | 5799.4 |
| Labor cost | 511.7 | 374.4 |
| Electricity | 7.8 | 46.9 |
| Depreciation Cost | 418.1 | 436.8 |
| Total running costs per hectare | 7301.9 | 6702.4 |
| Total running costs per Tree | 26.3 | 24.1 |
| Water Use Efficiency | | |
| Water consumption ($m^3$/tree/year) | 67.0 | 24.0 |
| Water consumption ($m^3$/tree/ha/year) | 18652.8 | 6681.6 |
| Revenue (USD) | | |
| Production from each date palm (ton) | 0.080 | 0.100 |
| Yield (ton/hectare) | 22.2 | 27.8 |
| Average Price for date palm fruit per ton | 780.0 | 780.0 |
| Revenue per hectare | 17333.3 | 21666.7 |
| Profit (USD) | | |
| Profit per hectare | 10031.4 | 14964.2 |
| Profit per tree | 39.7 | 57.1 |
| Profit per $m^3$ of water | 0.0541 | 0.1121 |

### Sap flow and evapotranspiration

As shown in Fig. 4, the data for winter season shows that the amount of crop water requirement ($ET_c$) obtained through SF, representing actual water consumption by the Naghal palm, was less than estimated $ET_c$ amount through PM model by 50.1 for AIF and 49.5% for BIF. Similarly, during summer season, the $ET_c$ obtained through the SF was less than estimated $ET_c$ through the PM model by 34.3 and 27.8% for both farms AIF and BIF, respectively. These findings demonstrated that the soil-plant-atmosphere based real-time water status monitoring through the use of state-of-the-art sensors for first time in Oman has shown that the PM-ET model has overestimated crop water requirements for the studied Naghal palm variety compared to actual needed water requirement for that tree.

### Stem water potential and sap flow

Sap flow rates (SF) showed an inverse relationship with stem water potential (SWP) (Fig. 5). Additionally, the two different irrigation systems had different impacts on SWP, where the AIF system made the Naghal palm suffer from

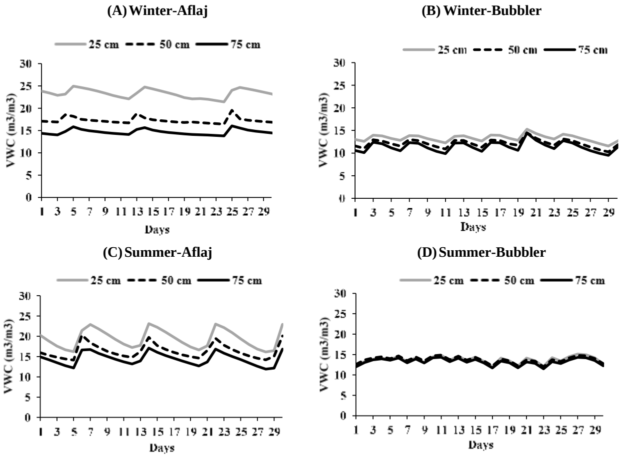

**Fig. 2:** Daily volumetric water content (VWC) at 25, 50 and 75 cm soil depths in AIF and BIF for (**A**) Winter-Aflaj, (**B**) Winter-Bubbler, (**C**) Summer Aflaj and (**D**) Summer Bubbler

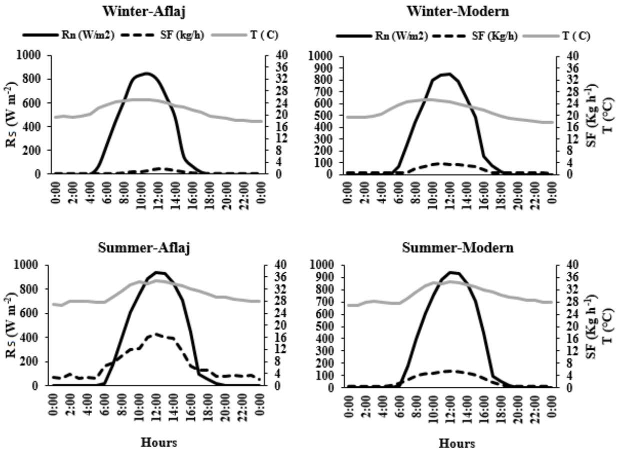

**Fig. 3:** Hourly relationship between sap flow rate (SF), mm/d and climate factors; solar radiation ($R_s$), W/m$^2$ and air temperature (T), C, for Aflaj and bubbler systems measured on date palm trees in summer and winter

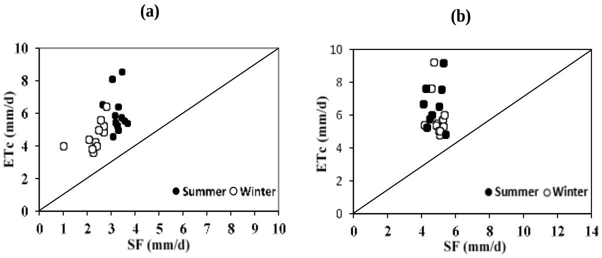

**Fig. 4:** Relationship between sap flow rates (SF), mm/d, and crop evapotranspiration (ETc, mm/d) for (**a**) Aflaj and (**b**) bubbler farms irrigation systems. White circles for winter data and black circles for summer data.

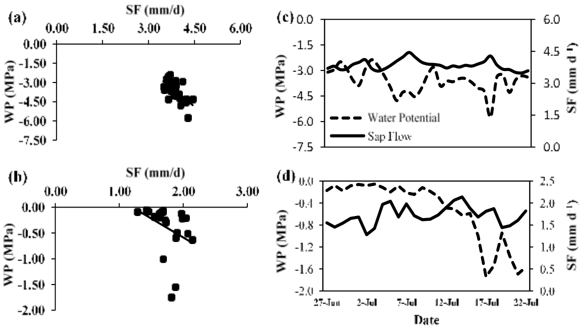

**Fig. 5:** Daily summer season trend (**a** and **b**) and variations (**c** and **d**) of water potential (WP) in relation to daily mean sap flow rates (SF) for Aflaj (**a** and **c**) and bubbler (**b** and **d**) irrigated farms

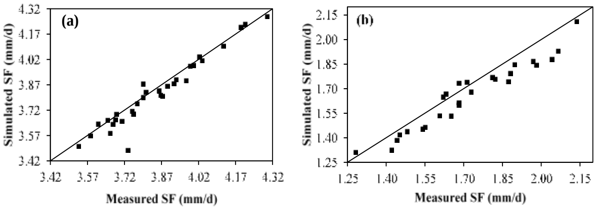

**Fig. 6:** Relationship between measured and simulated sap flow rates using Eq. 7 for (**a**) Aflaj and (**b**) bubbler system

water stress, resulting in SWP to decrease to around -5.8 MPa (Fig. 5a), while the BIF system maintained SWP at its optimum level by not exceeding -1.7 MPa (Fig. 5) as more negative values in water potential indicates more plant water stress (Milliron *et al.* 2018). On other hand, stem water potentials fluctuations were noticed more at AIF, with maximum fluctuation of -2.3 MPa, than at the BIF, with maximum fluctuation of -0.8 MPa, implying that BIF system was able to establish precise and steady water application than AIF.

## Water saving

Table 2 shows how the changing the traditional Aflaj irrigation system into a modern bubbler system has contributed in saving 77 and 79% of supplied water to farm during summer and winter, respectively. These water savings have increased into 92 and 91% after combining the change of irrigation system with the use of the smart monitoring system. On other hand, applying the smart monitoring system in the soil-plant-atmosphere continuum has also enhanced the water saving for the same irrigation system. Table 2 shows that the use of smart system in the AIF has saved 72 and 89% of irrigation water consumption during summer and winter, respectively when compared to water consumption before introducing the smart system to this farm. Similarly, the use of smart system in the BIF has saved 65 and 59% of irrigation water consumption during summer and winter, respectively when compared to water consumption before introducing the smart system to this farm.

**Table 2:** Water savings for using intelligent system for precision irrigation water applications

| Water Application / Irrigation Type | Applied volume ($m^3$) for AIF | | Applied volume ($m^3$) for BIF | | Water savings at BIF than AIF (%) | | Water savings using the intelligent system for BIF over AIF (%) | |
|---|---|---|---|---|---|---|---|---|
| | Summer | Winter | Summer | Winter | Summer | Winter | Summer | Winter |
| Actual water applications | 123.8 | 46.1 | 28.8 | 9.6 | 77 | 79 | | |
| Water application based on the use of the intelligent system | 34.6 | 4.8 | 9.9 | 3.9 | | | 92 | 91 |
| Water savings due to using the intelligent system (%) | 72 | 89 | 65 | 59 | | | | |

**Table 3:** Pearson's correlation between sap flow rate and meteorological factors

| Meteorological factors | $R_s$ (W $m^{-2}$) | T (ºC) | VPD (kPa) | U (m $s^{-1}$) |
|---|---|---|---|---|
| Correlation coefficient (R) - Aflaj | 0.74** | 0.85** | 0.73** | 0.37* |
| Correlation coefficient (R) - Bubbler | 0.76** | 0.81** | 0.63** | 0.22* |

$R_s$ - solar radiation, T - air temperature at 2 m, VPD - vapor pressure deficit, U - wind speed and (samples) n=31. *$P < 0.01$; **$P < 0.05$

**Table 4:** Regression statistics measured and simulated for two consecutive years

| Farms | R-Square | Intercept | a | b | SS | MS |
|---|---|---|---|---|---|---|
| BIF | 0.933 | -1.7724 | 0.00683 | 0.00632 | 0.8625 | 0.4312 |
| AIF | 0.941 | 11.3105 | 0.5525 | 2.2849 | 2525.26 | 1262.63 |

a and b = Coefficients, SS= Sum of Squares, MS= Means of Squares

### Sap flow prediction and validation

An empirical formula was derived by regression analysis of measured 2015 and 2016 data of SF with $R_s$ and T for both AIF, with $R^2 = 0.882$, and BIF, with $R^2 = 0.710$.

$$SF = aR_s + bT + c \qquad (7)$$

Equation 7 was used to simulate SF rates of 2017 for AIF as well as for BIF using unit less coefficients a, b, and c in addition to the recorded values of $R_s$ and T. The estimated daily SF rates were validated using the observed data of 2017 with a correlation value of $R^2 = 0.941$ for AIF (Fig. 6a) and $R^2 = 0.933$ for BIF (Fig. 6b). The regression equation data sets are presented in Table 4.

### Socio-economic analysis

The socio-economic analysis results are presented in Table 1. Despite the low quantity of water used in the bubbler irrigation the yield in the BIF farm (27.8 tons/hectare) was 20% higher compared to the AIF yield (22.2 tons/hectare). The profit per cubic meter of water increased from 0.054 USD under AIF to 0.112 USD under BIF system. On the other hand, each Naghal palm irrigated with AIF did cost 26.3 USD per Naghal palm but the cost was only 24.1 USD per Naghal palm under the BIF. The tree costs covered pollination, cutting off its old leaves and offshoots, rearranging the fruit bunches and other processes to ensure keeping up the tree in good shape and ready for good production. Other costs were needed for running the farms such as labor work, electricity and fertilizers as well as the depreciation costs of materials resulted an overall cost for AIF with 7,302 USD per hectare per year in comparison to 6,702 USD for BIF. The Naghal palms generated a total profit of 10,031 USD/ha under AIF whereas, BIF generated 14,964 USD/ha. More precisely, results revealed through farm survey questionnaire and water applications that the profit per tree for the BIF was 59.87% higher than AIF. The socio-economic analysis results of this study revealed that the smart monitoring system along with the instrumentations used in this study enabled us to analyze, examine and have a clear and continues view on how the bubbler irrigation system was more precise and efficient in comparison to the traditional/flood/Aflaj irrigation system.

## Discussion

Correlations between SF and climatic factors T, Rs, and VD with $R^2$ = 0.73, 0.86, and 0.61, respectively, for Olive trees irrigated with BIF in Tunisia were reported by Amani *et al*. (2013). On the other hand, Pereira *et al*. (2007) were able to determine one single coorelation bewteen combined SF of four trees; dwarf apple, olive tree, walnut and large apple, and $R_s$ with with $R^2 = 0.92$. Pei *et al*. (2019) also determined similar combined correlation between the climate factors T, VPD and Radiation and SF but with $R^2 = 0.7$. Hence, it is clear that climate conditions with these major factors; $R_s$, T, VPD and U do play an important role in affecting tree transpiration rates (Hatfield and Dold 2019).

Sap flow and evapotranspiration revealed that SF measures the plant transpiration through plant xylem, and $ET_o$ combines two important phenomena, the water transpiration from leaves and direct evaporation from soil (Amani *et al.* 2013). Therefore, SF was directly affected by $ET_o$ and so by $ET_c$, as $ET_o$ largely depends on weather conditions, especially $R_s$, VPD, U and T (Er-Raki *et al.* 2009). $ET_c$ depends on $ET_o$ and Kc factor (equations 1 and 2). Similar to our findings in this study, (Ferraz *et al.* 2015) found that PM based evapotranspiration overestimated the water consumption as compared to SF transpiration which precisely estimated the actual plant water requirement through xylem of papaya trees in Brazil which helped in delivering accurate irrigation water to the trees to enhance the water productivity.

Stem water potential and sap flow trends signified by the plant-based water stresses monitoring approaches using SWP and SF measurements have been considered as the most suitable irrigation water monitoring system especially during summer (Ahiman *et al.* 2017). In addition, the real-time system can monitor the soil-water availability with SWP as a water deficit or over-irrigation indicator through recording continuous fluctuations in physiological reforms inside plants (Othman *et al.* 2014). Therefore, the integration of SWP and SF provides a valuable hi tech tool that can assist in triggering the irrigation system to start or cut-off to water demand in response to climate variations and so relieve plants from water stress (Corell *et al.* 2016; Ahumada-Orellana *et al.* 2017). Moreover, the plant based real-time monitoring system demonstrated how it can help to obtain precise and actual estimates of plant water-use for precision irrigation when combining the SF and SWP with bubbler system in reducing excessive water us.

Water saving results revealed that the use of bubbler system with real-time monitoring lead to a proper irrigation scheduling for precision irrigation water application which can recover excessive water applications (Table 2). Elnemr (2020) reported the real-time monitoring with controlled irrigation water applications have effectively enhanced the crop water productivity and helped to conserve water and energy resources. However, our study has also investigated the efficiency in water saving using the soil-plant-atmosphere real-time smart monitoring system even with no change of irrigation from traditional to modern system.

## Conclusion

This study revealed that advance technology, instrumentation and monitoring systems have the ability to track tree responses for following parameters: weather, water status, moisture levels, soil conditions and water stress. Furthermore, it displayed a significant potential for measuring the combined plant factors such as plant vigor, production efficiency, nutrient-water uptake volume and timing. The $ET_c$ values for both winter and summer seasons were higher compared to SF by 49 and 31% for aflaj and bubbler irrigated farms, respectively. The results showed intriguing findings where commonly practiced $ET_o$ model overestimated water requirement compared to actual needed water requirement for the crops. Combining modern bubbler system with the smart real-time monitoring reduced water consumption by 92 and 91% during summer and winter seasons, respectively. The empirical model derived in this study was able to simulate sap flow rates using $R_s$ and T data with $R^2 = 0.941$ for Aflaj and for bubbler irrigation farm with $R^2 = 0.933$. The financial analysis showed that bubbler/micro irrigation system gave more crop yield and farm revenue. Hence, the usage of these tools in finding actual water requirement through plant/soil-based monitoring revealed valued applications in water saving and precision agricultural farming. This showed the practical utility of such innovative technology in modern agriculture in order to reduce water wastage and therefore increased the crop yield.

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## Author Contributions

Sajjad Ahmad Siddiqi: Conceptualization, resources, validation, investigation, visualization, formal analysis, writing original draft, review and editing. Yaseen A Al-Mulla: Conceptualization, resources, validation, investigation, visualization, formal analysis, review and editing. Ghazi AbuRumman: Review and editing. Makram Belhaj: Review and editing. Slim Zekri: Conceptualization, review and editing. Abdulrahim Al-Ismaili: Review and editing. Sadik Rahman: Review and editing.

## Conflict of Interest

The author declares no conflict of interest of any sort.

## Data Availability

The reported data can be made available upon requesting to the corresponding author, Dr. Yaseen A Al-Mulla.

## Ethics Approval

Not applicable

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