Irrig. and Drain. **(2020)**

ACTUAL WATER USE OF YOUNG DATE PALM TREES AS AFFECTED BY AMINOLEVULINIC ACID APPLICATION AND DIFFERENT IRRIGATION WATER SALINITIES†

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ABSTRACT

The Arabian Gulf countries are facing unprecedented water management challenges owing to limited water resources and salinization of the soil. Date palm trees represent a crucial socio-economic asset in the region. Improving water productivity and tolerance to salinity are the most viable options. A split plot experiment was conducted on 4-year-old date palm trees in concrete lysimeters. The objective was to study the effects of aminolevulinic acid (ALA) and different irrigation water salinities (EC) on actual water use (ET) and irrigation efficiency (IE). Low: < 1, medium: 12–15 and high: 18–20 (dS m^{-1}) EC were used as main plots while zero and 5 ml per tree of ALA represent the subplots. Data were collected during the period between June 2016 and September 2017. Results indicated that ALA application significantly increased tree ET by about 7%. Medium and high EC levels masked the effect of ALA on ET. EC significantly reduced ET by about 70 and 83% for high and medium EC respectively. The highest ET was obtained under low EC with ALA. Highest IE (63%) was obtained under low EC with ALA, followed by 48% for low EC without ALA. All ALA treatments resulted in higher IE compared with no ALA. © 2020 The Authors. Irrigation and Drainage published by John Wiley & Sons Ltd on behalf of International Commission for Irrigation and Drainage

KEY WORDS: date palm; salinity; aminolevulinic acid; water use; lysimeters

Received 29 April 2019; Revised 15 December 2019; Accepted 20 December 2019

RÉSUMÉ

Les pays du Golfe font face à un problème de gestion de l'eau sans précèdent. Ce problème est dû aux ressources limitées en eau et à la salinisation élevée des sols. Les palmiers dattiers représentant un enjeu crucial dans la région, ainsi l'amélioration de l'efficacité en matière d'irrigation et de leur tolérance à la salinité constituent des défis importants. Une expérimentation de culture fractionnée a été réalisée sur des palmiers âgés de 4 ans dans des lysimètres. L'objectif était d'étudier les effets de l'acide aminolévulinique (ALA) ainsi que de la variation de la conductivité électrique (EC) sur la consommation réelle en eau (ET) ainsi que sur l'efficacité de l'irrigation (IE). Des taux faibles, < 1, moyens, 12–15, et élevés 18–20 (dS m^{-1}) de EC ont été utilisés sur les parcelles principales tandis que des quantités de 0 à 5 ml d'acide par arbre l'ont été sur les sous-parcelles. Les résultats indiquent que l'ajout d'acide ALA a fait augmenter le taux de ET des arbres d'environ 7%. Les degrés moyen et élevé de salinité ont quant à eux masqué les effets de l'acide sur le degré de ET. Le degré de salinité de l'eau a significativement réduit le taux de ET de 70 et de 83% respectivement pour les hautes et basses salinités. L'ET le plus le plus élevé a été obtenu avec des faibles taux de salinité et d'acide. © 2020 The Authors. Irrigation and Drainage published by John Wiley & Sons Ltd on behalf of International Commission for Irrigation and Drainage

MOTS CLÉS: palmiers dattiers; salinité; acide aminolévulinique; irrigation; lysimètre

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†Irrigation des jeunes palmiers dattiers affectés par l'acide aminolévulinique et soumis à différents degrés de salinité.

Contract/grant sponsor: Sultan Qaboos Chair in Desert Farming, Arabian Gulf University; contract/grant number: STS NRE 001 2015

1. INTRODUCTION

Scarcity of water together with primary and secondary salinization of agricultural lands represents a daunting challenge for sustainable agricultural production all over the world. Additional water management burdens are inflicted on arid and semi-arid regions experiencing high temperatures, meagre water resources and soil salinity (Haj-Amor *et al*., 2017). Recently, the strong and complex interlinkages between water–food–energy have added a new dimension, together with threats emanating from climate change. As agriculture is by far the largest consumer of water, improving water productivity remains one of the most viable and effective options in water management (Moreno-Pérez and Roldán-Cañas, 2013).

The Arabian Gulf countries have among the world's lowest absolute and per capita water resources (Osman *et al*., 2010). In addition, some of these countries are overexploiting their water resources by about 10–20% (Odhiambo, 2017). As the region is also characterized and dominated by non-renewable groundwater resources, the total per capita renewable water resources range between 86.5 (m^3 yr^{-1}) for Saudi Arabia down to 7.7 and 6.2 (m^3 yr^{-1}) for Bahrain and Kuwait respectively. On the other hand, Dawoud (2017) reported that groundwater abstraction in the Gulf Cooperation Council (GCC) countries represents about 78% of the water resources, while desalination and reuse of treated sewage effluent (TSE) represent about 16 and 6% respectively. Similarly, Esra and Al-Zubari (2017) reported that the ratio of TSE to groundwater utilization in the GCC countries does not exceed 9%. One of the obstacles delaying full utilization of TSE in agriculture, apart from acceptance, is the variable resultant quality due to several reasons, such as surpassing the maximum operational capacity (Esra and Al-Zubari, 2017) and ageing treatment plants. This may lead to the supposition that groundwater resources will continue as the main source for agricultural production in GCC countries.

Salinization of groundwater, on the other hand, could occur due to overexploitation, seawater intrusion, bad agricultural practices and seepage of high-saline water resulting from oil extraction. Other reasons may include land disposal of rejected brine water with EC ranging between 13 and 30 mS cm^{-1} (Mohamed *et al*., 2005), in addition to lack of proper treatment of both wastewater and agricultural drainage water that may find their way into shallow or deep groundwater aquifers. Generally, salinity impairs plant water uptake by creating adverse osmotic potential conditions in the soil solution around the root zone. Other damage caused by salinity is related to ion toxicity that prevents sequestration of sodium ions into the vacuoles (Alhammadi and Kurup, 2012). The Food and Agriculture Organization of the United Nations (FAO) (2002) reported that date palm yield could be lost completely when soil and irrigation water salinities reach 32 and 21 dS m^{-1} respectively.

Date palm (*Phoenix dactylifera*) is one of the most important fruit trees that can withstand harsh desert climatic conditions and high salinity levels. Zohary *et al*. (2012) reported that date palm was one of the principal fruit crops domesticated in the old world. Its origin could be related back to 4000 BC in southern Iraq, Mesopotamia. El-Juhany (2010) reported that the Arab world has about 70% of the world's date palms and contributes about 67% of global date production. Date palm trees and dates have important socioeconomic and spiritual value in the Islamic world, especially during the fasting month of Ramadan. Several studies have been conducted on the crop water requirements and/or effects of salinity on date palm (Mohamed *et al*., 2005; Alamoud *et al*., 2012; Bhat *et al*., 2012; Green *et al*., 2014; Dewidar *et al*., 2015). Most of the presented results indicated that date palm could tolerate high salinity levels with daily water use of around 7–14.6 mm during summer and 2–4 mm during winter.

On the other hand, the effects of 5-aminolevulinic acid (ALA) have been studied in various crops (Jia *et al*., 2016; Wu *et al*. 2018), including young and mature date palm trees (Hotta *et al*., 1997; Youssef and Awad, 2008; Memon *et al*., 2009; Mohamed and Al-Qurashi, 2011; Darwesh and Rasmia, 2013). Generally, the main effects of low concentrations of ALA were attributed to enhancement of chlorophyll *a*, leading to improved photosynthesis and inhibition of dark respiration in addition to enhanced nitrite reductase activities. ALA was also reported in some of these studies to help plants tolerate various environmental stresses such as salinity and drought. The ALA-based fertilizer known as Pentakeep-v was concluded by Youssef and Awad (2008) to improve salt tolerance of young date palm seedlings by increasing photosynthetic assimilation. However, Mohamed and Al-Qurashi (2011) showed that ALA application at different rates had different responses from young tissue-culture-derived date palm trees. Some of the effects such as tree height needed 20 months to significantly distinguish the treated trees from the control. On the other hand, their study showed that chlorophyll *a* concentration was significantly higher in date palm leaves treated with 50 and 100 ppm of ALA, while chlorophyll *b* concentration did not show significant differences at the 50, 100 and 150 ppm tested concentrations of ALA. They also concluded that the higher concentration (150 ppm) of ALA application did not show a significant effect on tree growth parameters or chlorophyll *a* concentration.

This research was conducted to study the effects of ALA on actual water use, irrigation efficiency and tolerance to different levels of irrigation water salinities up to 20 dS m^{-1} under the harsh arid climatic conditions of the kingdom of Bahrain.

2. MATERIALS AND METHODS

2.1. General experimental set-up

The experiment was conducted using 20 non-weighing concrete lysimeters during the period of 20 June 2016 to 6 September 2017 in the field of the Arabian Gulf University in Bahrain. Lysimeter dimensions were 1 m width by 1 m length by 0.70 m depth. The last 5 cm were filled with small gravel to facilitate drainage. The lysimeters were equipped with drainage pipes attached to plastic bags to collect drainage water. Diviner 2000 access tubes were installed in the centre of each lysimeter for moisture measurement and monitoring. Each lysimeter was also equipped with EC, soil moisture and temperature sensor type 5TE placed at 30 cm depth and connected to a battery-operated Decagon (EM50) data logger. A Diviner 2000 moisture meter was calibrated in the lysimeter soil and the soil pF curve was determined during a previous study (Buftain, 2012). Figure 1 shows the results of the calibration of the Diviner 2000.

An automatic weather station was installed beside the lysimeters and provided all the relevant weather data through a web-based Field Climate application since January 2012. In addition, the station provided data on daily reference evapotranspiration according to the Penman–Monteith method. About 6-month-old date palm trees were transplanted in the lysimeters on 28 November 2012. The trees were regularly irrigated with nutrient solution in order to be established until about 3 months before the start of the experiment on 20 June 2016, when manual irrigation was practised until completion of the bubbler irrigation system at the start of the experiment. Thereafter, a regular fertilizer programme was followed at the rate of 35 g per tree of nitrogen in the form of urea, $CaNO_3$ and NPK (15 : 30 : 15) which was mixed with irrigation water during the period 13–27 April 2017. The mentioned doses contained 15 g per tree of P and 7.5 g per tree of K. In addition, 2.5 g per tree of micronutrients were also added. Three irrigation tanks were installed to provide the different irrigation water salinities required for the experiment. All the tanks used the same main water source with EC < 1 dS m^{-1}. It is worth mentioning here that in all the period prior to the start of the experiment, the main water source salinity was about 3 dS m^{-1}. Each tank was connected to the relevant trees through a 0.5 HP electric pump with a bypass for return flow to the tank to facilitate mixing of the salts and allow for manual timing control of water application. The desired salinity levels were obtained by adding sodium chloride and adjusting EC to the required levels which were confirmed by a portable EC meter before each irrigation event. The amount of applied irrigation water per tree was calculated from a relationship obtained by calibration of different times of applications in minutes against the collected volume in litres. A special bucket with a drainage tube was designed for the purpose of the irrigation water calibration. Figure 2 shows a schematic vertical cross section diagram of the design used for the calibration. Regression equations were derived from the calibration data of the lysimeters to transfer irrigation times into irrigation volumes. Irrigation water was applied to each treatment from the relevant tank using a 0.5-inch PVC main line and a 13 mm line to deliver irrigation water to each tree (lysimeter) via a bubbler. Control valves were installed to facilitate irrigation time application and delivery of water as per each treatment with its replications (three replications). Irrigation timing and interval were set according to the soil moisture profile of each lysimeter as indicated by the moisture depletion graph displayed on the Diviner 2000 meter screen. A general rule of thumb regarding the depletion shape implies that a treatment needs irrigation if two of the three trees showed a change in the slope of the moisture depletion curve, indicating that soil moisture had started to become a limiting factor in ET. On the other hand, straight-line moisture depletion indicates no soil moisture stress. The Diviner meter screen is capable of displaying 2 weeks' data including the most recent readings. In addition, it can also display individual soil moisture depths, thus becoming a handy tool for monitoring soil moisture and for decisions on when and how much to irrigate bearing in mind the determined soil texture and the pF curve. The calculated total applied water in litres for each treatment was averaged for each of the three replicates transformed into mm depth and used in the analysis.

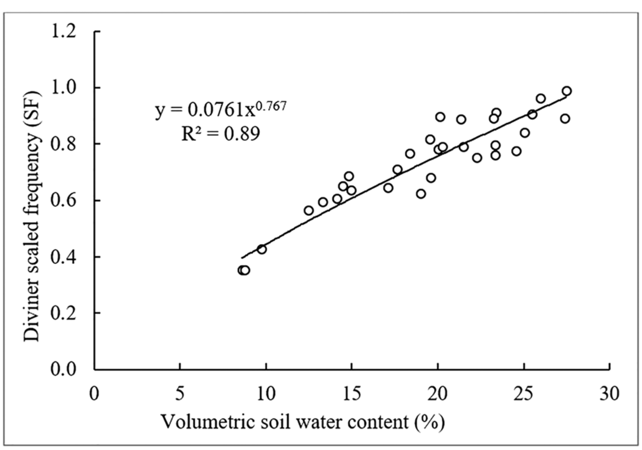

Figure 1. Diviner 2000 calibration carried out in the lysimeter soil (source: Buftain, 2012)

2.2. Experimental design

The experiment was laid out in a split-plot design with irrigation water salinity as main plots and application of ALA in the form of Pentakeep Super as subplots. There were three irrigation water salinity treatments: low, EC < 1; medium, 12–15 and high, 18–20 dS m^{-1}. ALA application was either

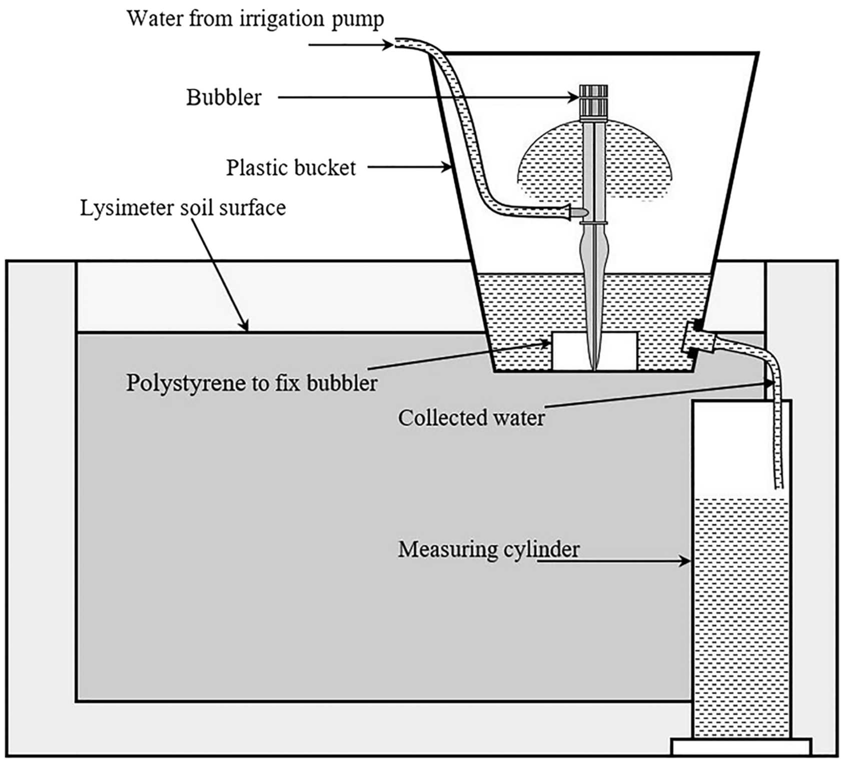

Figure 2. Set-up used for the calibration of irrigation water (not to scale)

5 ml per tree every 10 days ±4 days or without ALA application. Each treatment was replicated three times. Thus, there were 18 trees each in one lysimeter. In addition, there are other two trees (number 16 and 21) that were given the high EC irrigation water and the soil surface was covered tightly around the tree trunks by 5-cm thick polystyrene to prevent evaporation from the soil surface for the calculation of transpiration. The results of transpiration and salt movement in the soil profiles will be discussed in another paper. Figure 3 shows a schematic diagram of the experimental layout. Table I shows some important physical and chemical properties of the lysimeters' soil. Table II shows the nutrients content of Pentakeep Super, while Table III shows the average relevant weather parameters during the experiment.

2.3. Data collected

Soil moisture readings were taken using the Diviner 2000 meter on almost a daily basis. In any irrigation event, care was taken to record soil moisture just before water application and then after all the applied water had infiltrated into the profile, i.e. when no free-standing water was left on the lysimeter surface. Thereafter, the moisture readings were taken in the early morning on almost a daily basis. Decisions on irrigation events were based on soil moisture depletion shape as monitored on the screen of the Diviner 2000 meter. Thus, for any irrigation cycle, if n denotes the number of irrigation cycles, (θw_n) represents post-irrigation reading while (θd_n) represents the last reading taken at the end of the same irrigation cycle. All the other daily moisture readings between (θw_n) and (θd_n) represent variable moisture contents reflecting the depletion pattern that is dictated by crop water use according to the prevailing soil moisture and weather conditions. The Diviner 2000 recorded soil moisture data on an incremental basis of 10 cm depth. Hence, there were six incremental depths (0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm) which were summed up to provide the total lysimeter profile moisture content in mm. All the moisture data were downloaded on a regular basis from the Diviner 2000 and stored in an Excel file for the calculation process.

Initial soil samples were taken from each lysimeter for paste extract calculation of soil salinity before the start of the experiment. One lysimeter was found with a soil EC of about 6 dS m^{-1} and was immediately subjected to leaching until its EC was lowered below 3 dS m^{-1}, similar to all the other lysimeters. All the relevant weather data were downloaded from the Field Climate website that included hourly rainfall data and daily reference crop evapotranspiration (ET_0) covering the experimental period.

As a preliminary we tested six methods for chlorophyll extraction and calculation using a spectrophotometer. The methods were based on a review of literature such as the Hiscox and Israelstam (1979) method that uses incubation

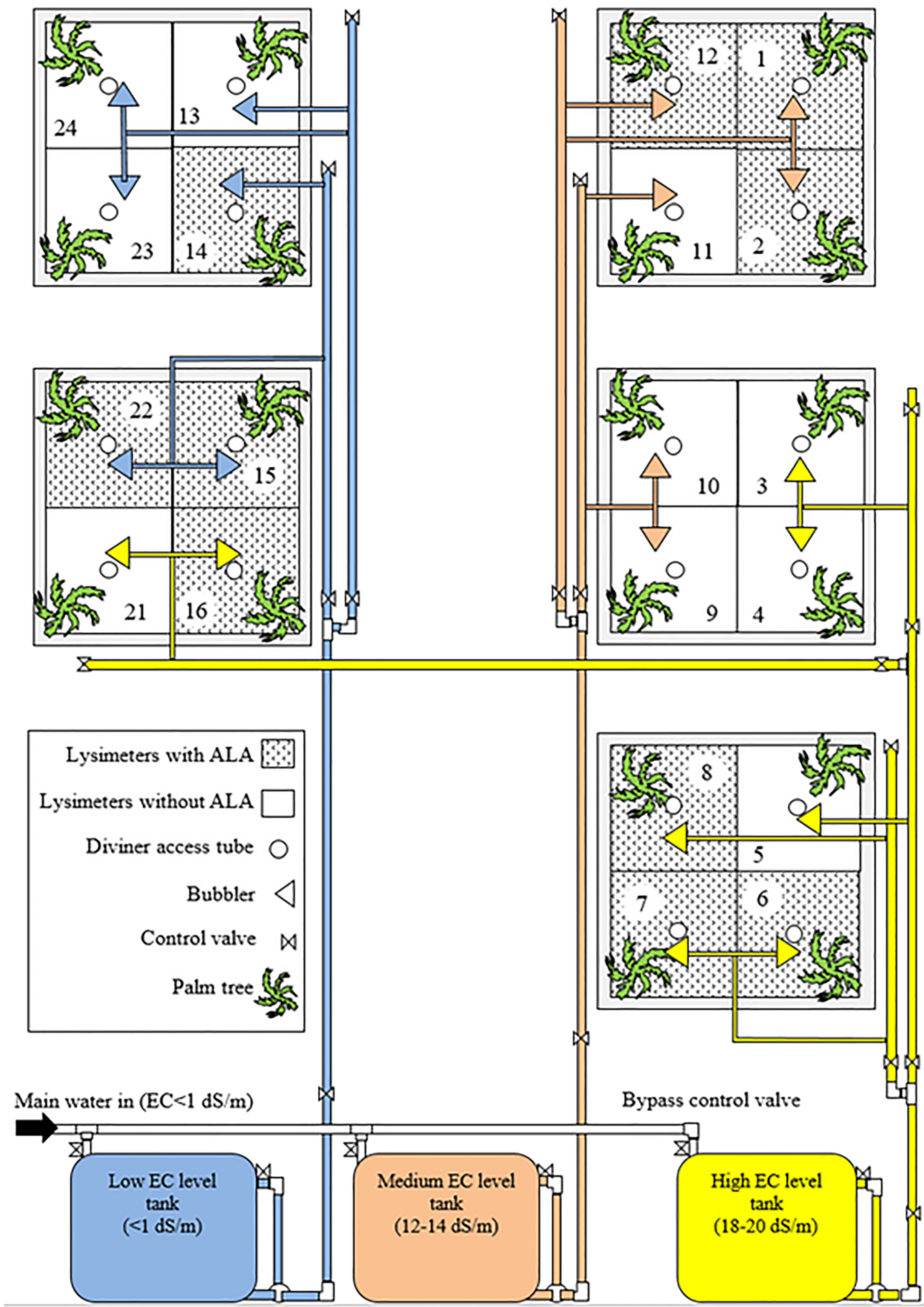

Figure 3. Schematic diagram of the experimental layout [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Lysimeters' soil physical and chemical properties

Property	Description
Sand (%)	84
Silt (%)	5
Clay (%)	11
Soil texture class	Loamy sand
EC (1 : 5)	4.5 dS m^{-1}
pH (1 : 5)	7.88
Irrigation water EC (dS m^{-1})	<1 dS m^{-1}

Table II. Macro- and micronutrient contents of 5-aminolevulinic acid (%)

Nutrient	%	Nutrient	%
Total nitrogen (N)	8.0	Iron chelated by DTPA	0.29
Ureic nitrogen (N)	5.0	Manganese (Mn)	0.12
Phosphorous pentoxide (P_2O_5)	5.0	Boron (B)	0.07
Nitrate nitrogen (N)	3.0	Zinc (Zn)	0.07
Potassium oxide (K_2O)	3.0	Copper (Cu)	0.01
Magnesium oxide (MgO)	3.0	Molybdenum (Mo)	0.01
Iron (Fe)	0.29		

All nutrients are in water-soluble forms.

of samples in dimethyl sulphoxide (DMSO) at 65 °C overnight, but the method did not work probably due to the high degree of cutinization and thickness of date palm leaves. Xueyun *et al*.'s (2013) method that include brief boiling of leaves before extraction using 80% acetone was also used. We also used grinding and soaking in 80% acetone with or without overnight refrigeration. According to the results, we used overnight soaking in 80% acetone at room temperature and Arnon's (1949) calculation method for chlorophyll *a* and *b*. For carotenoid calculation, we used the Ridley (1977) method. Accordingly, ten leaves from about a similar age (the second circular row from the growing tip) were taken from each tree and immediately wrapped in aluminium foil and stored at 4 °C for chlorophyll analysis. The chlorophyll extraction was performed on leaf samples taken on November 2016 and January 2017.

All the data were statistically analysed as a split-plot design using JMP, SAS institution Version 7.0. The two factors (water salinity and ALA) and their interactions were determined and their mean separations were carried out using the least squares means student's *t* test. Although applied water was provided using similar application times for each treatment based on soil moisture status, we analysed the applied water of all the irrigation cycles to help in interpretation of results, especially those of IE. This was of great importance since the design of the irrigation system does not imply that the trees receive the same amount of applied water due to different friction losses caused by the experimental layout.

2.4. Calculations and observations

The soil water balance equation of the lysimeter can be written as

$$P + I – \mathrm{ET} – R – \mathrm{DW} \pm \Delta W = 0 \qquad (1)$$

where P is precipitation (mm), I is irrigation (mm), ET is evapotranspiration (mm), R is runoff which is zero as the

Table III. Average monthly weather data during the experiment, rainfall is total (mm)

Month	Solar radiation (MJ m^{-2})	Rainfall (mm)	Wind speed (m s^{-1})	Temp. (°C)	RH (%)
Jun. 2016	26.0	0.00	1.26	40.8	37.0
Jul. 2016	22.7	0.00	1.21	36.8	45.6
Aug. 2016	19.5	0.00	0.75	37.0	52.3
Sep. 2016	16.4	0.00	1.00	34.3	52.8
Oct. 2016	13.3	0.00	0.74	29.5	55. 9
Nov. 2016	12.3	8.00*	1.01	25.1	67.0
Dec. 2016	14.9	0.20*	1.39	19.8	70.4
Jan. 2017	13.1	0.00*	1.24	18.6	71.7
Feb. 2017	13.8	2.60*	1.21	16.7	69.7
Mar. 2017	15.1	39.40	0.77	21.7	69.5
Apr. 2017	25.3	0.00	1.49	39.5	38. 8
May 2017	23.1	0.00	1.12	33.4	39.0
Jun. 2017	25.2	0.00	1.36	39.8	39.0
Jul. 2017	22.0	0.00	0.60	37.9	43.1
Aug. 2017	19.1	0.00	0.56	37.6	52.6
Sep. 2017	16.3	0.00	0.49	35.2	56.5

*Erroneous rainfall data due to rain gauge malfunction (restored on 25 February 2017).

water is bound in the lysimeter surface until it infiltrates, DW is drainage (mm) and ΔW is change in soil moisture (mm). It is important to mention here that knowing the lysimeter surface area, the volumetric water measurement in litres can be transferred into mm depth. In the event of rainfall, any that occurred during the night before the Diviner 2000 reading will be included in the soil moisture reading that is usually taken between 7:00 and 9:00 am on a daily basis (ET is supposed to be negligible during the night, so it was ignored). Rainfall that occurred after the reading in the daytime would be added to ET after ΔW is determined. Thus, in the case of rainfall events, crop ET was determined on a case-by-case basis using the rain gauge hourly data combined with the Diviner 2000 soil moisture data, which also includes the time of moisture reading. In 2016 prolonged rainy days had occurred during the period 25 November to 7 December 2016 which coincided with irrigation cycle number 19, and again during 18–29 December 2016 they coincided with irrigation cycle number 20. Unfortunately, after downloading the data it was noticed that the rain gauge was not giving reliable data compared with the visually observed rainfall during these two periods. For example, during late November 2016 the station recorded only 8 mm compared with 47.6 mm obtained from the Bahrain main weather station that was about 10 km from the experimental site. The rainfall gauge was then calibrated according to the guidelines of the manufacturer on 25 February 2017. Thereafter, the rainfall data were restored without further problems. Since it was impossible to apply the water balance equation during these two irrigation cycles, the calculations of actual water use (ET) during these two cycles (19 and 20) were omitted from the analysis. It is important to mention here that apart from the two omitted irrigation cycles, the maximum hourly rainfall encountered during 2016 was 6.8 mm at 17:00 pm and 10.4 mm in March 2017 at 03:00 am. Since the trees are well pounded by plastic sheets on the lysimeter edges, we were sure that no runoff occurred from the lysimeters' surface. The amount of hourly rainfall together with the nature of the trees' open canopy allowed us to ignore interception losses. Hence, we omitted the need to determine the effective rainfall, bearing in mind that any drainage event was accounted for through the visible plastic bags attached to the drainage tubes.

When there was no rainfall and no observed drainage (which was the dominant condition for most of the irrigation cycles), actual evapotranspiration during any irrigation cycle (ET_n) can be obtained as follows:

$$ET_n \text{ (per irrigation cycle)} = \left(\sum_{i=1}^{6} \theta_w - \sum_{i=1}^{6} \theta_d \right) \quad (2)$$

where $\sum_{i=1}^{6} \theta_w$ is the sum of the moisture contents of the six soil incremental layers obtained by the Diviner 2000 just after any irrigation is given (mm); $\sum_{i=1}^{6} \theta_d$ is the sum of the same soil moisture layers at the end of the same irrigation cycle. It is important to mention here that, to obtain ET in mm day^{-1} the result of any ET calculation is divided by the number of days representing the irrigation cycle excluding the last day. This was done knowing that all the readings were taken early in the morning and the new irrigation cycle will start just after post-irrigation Diviner readings, i.e. 30–40 min for free water to disappear from the loamy sand soil of the lysimeters. Thus, the last day in each irrigation cycle will be counted in the new irrigation cycle.

It was observed early during the summer months of 2017 that the low EC treatments (with and without ALA) used and needed more water compared with the medium and high EC ones. This was evident from the early curvature of the moisture depletion line observed in the screen of the Diviner 2000 and rapid drying of the soil surface layer. In contrast, the medium and high EC treatments showed a wet soil surface as salt accumulation started to reduce the ability of roots to take up water and accordingly, the amount of applied water was reduced to avoid leaching and deep drainage in those EC treatments. Thus, after irrigation number 34 (333 days from the start of the experiment) and based on the Diviner readings, the low EC treatments received additional irrigation in-between almost any two irrigation cycles of the medium and high EC ones in 2017. At the start of the experiment and up to irrigation number 10 (65 days) all the treatments received 7 min irrigations in about 8–10-day intervals. This was equivalent on average to about 38–49 l per tree. Between irrigation numbers 10 and 35, more time of application (about 15 min) was used for the low EC treatments due to observed more water use. In contrast, less time of water application for EC treatments (about 3–7 min) was practised to avoid leaching of the salts. An exception was made for irrigation number 16 on 19 October 2016 when all the treatments received 10 min irrigation to test the system for drainage. The test confirmed the strategy of reducing time of application for the salinity treatments, as all the lysimeters under salinity treatments produced drainage water that was measured and included in the calculation of actual ET as well as the EC of drainage water. The total additional 10 irrigations given to low EC treatments after irrigation number 34 created a tricky situation in the calculations of actual water use (ET) and applied water per irrigation cycle. This was solved by summing up the extra irrigation event in terms of applied water and ET, giving rise to the same total (46) number of irrigations. This implied that all the data for applied water and ET calculation were analysed and presented for 46 irrigations excluding ET during the two omitted irrigations mentioned (19 and 20).

Various definitions have been used regarding water productivity such as irrigation efficiency (IE), water productivity (WP*) and physiological water productivity (PWP). Water productivity (WP) has also been used synonymously with irrigation water productivity (IWP). Such definitions were usually linked with the scope of the study and the area of specialty. For example, engineers are concerned with IE, decision makers with WP or IWP, breeders with PWP and agronomists with WP*. Therefore, care must be taken when comparing different water productivity figures. Also note that the International Commission on Irrigation and Drainage (ICID) has adopted the term 'water productivity' instead of 'water use efficiency' that has led to misinterpretations; therefore, in this context, and for the benefit of the subject and further discussion, the following explains those definitions:

$$\mathrm{IE} = \frac{\mathrm{ET}}{\mathrm{AW}} (\mathrm{ASCE}, 1978) \tag{3}$$

$$WP^{*} = \frac{DM\ \left(t\ ha^{-1}\right)}{ET\ (mm)} (Jensen\ et\ al., 1981) \tag{4}$$

$$PWP = \frac{Pt}{ET\ (mm)} (Sinclair\ et\ al., 1984) \tag{5}$$

$$WP\ or\ IWP = \frac{\mathrm{Y}\ \left(\mathrm{t\ ha}^{-1}\right)}{\mathrm{AW\ (mm)}} (Howell, 1994) \tag{6}$$

where ET is crop evapotranspiration, AW the total applied irrigation water including rainfall (units should be the same, either volume or depth for both ET and AW), DM is dry matter produced, Pt is photosynthesis and *Y* is crop yield. Other formulas were also used for PWP that include dry matter assimilation and transpiration.

In this research, we were interested in IE since much of the water losses are related to the great mismatch between applied water and water used in ET. In addition, providing such information on IE will help improve the design of date palm irrigation systems to narrow the gap between AW and ET under prevailing soil and desert climatic conditions.

The calculated ET values were analysed as the dependent variable for each irrigation cycle. Application of ALA (with and without) and the three levels of irrigation water salinities were analysed as the independent variables. Since the irrigation cycle number represents increasing salinity with time, and since each irrigation number had a complete set of measured applied water and calculated ET values, the irrigation number was also analysed as an independent variable. Similarly, the calculated total applied water was also analysed to better interpret the IE. Table IV shows the overall statistical analysis result as obtained by the JMP V 7.0 program excluding the total applied water, which was analysed separately.

Table IV. Overall statistical analysis results for actual water use (ET mm per irrigation)

Source of variation	DF	Sum of squares	*F* ratio	Prob. > *F*
Irrigation No. (Irr. No.)	43	20 900	25.9	<0.0001*
ALA treatments (ALA)	1	304	16.2	<0.0001*
Salinity treatments (EC)	2	145 000	3860	<0.0001*
Irr. No. by ALA	43	580	0.71	0.910
ALA by EC	2	452	12.0	<0.0001*
Irr. No. by EC	86	56 400	34.9	<0.0001*
Irr. No. by ALA by EC	86	1 690	1.04	0.381

3. RESULTS AND DISCUSSION

3.1. Irrigation number

The effect of irrigation number on ET is complicated by the effects of the different EC treatment applied water and weather conditions. Generally, a reduction trend with time due to the cumulative effect of salts caused by two treatments out of three can be seen during the early irrigation numbers. However, ET has increased in specific time spans that coincided with the heavy irrigation given on 19 October 2016 that resulted in drainage of 11 lysimeters. The same case occurred during two events of continuous cloudy and rainy days that coincided with the periods 1–21 February 2017 (irrigation number 24) and 15–28 March 2017 (irrigation number 27), when Bahrain main weather station recorded 93.6 and 40.5 mm respectively. The site weather station recorded only 2.6 (malfunction) and 30 mm respectively during the same periods, indicating a reliable second value that was obtained after the calibration. Figure 4 shows the trend of actual averaged water use (ET) with respect to the irrigation cycle number. The results could clearly explain the observed trends in overall ET with irrigation number. The first nine irrigations reflected a clear overall reduction trend in ET as a result of salt accumulation in two out of three water EC treatments, since the application time of irrigation water was the same for all the treatments. Irrigation number 10 witnessed a sudden increase in ET led by an overall increase in ET, as a result of doubling application time for the low EC treatments to satisfy rising ET demand in addition to recommencing ALA application for all the treatments. This was followed by an overall decline with time due to salt accumulation again, and a steady decrease in air temperature together with an increase in relative humidity towards the end of summer. Figure 4 also indicates the importance of light soil texture and rainfall events in increasing ET, probably by reducing salt concentration in the effective root zone for the medium and high EC treatments. This was clearly indicated by the observed ET peaks during the rainfall events coinciding with irrigations number 24 and 27. The slight increase in overall ET after irrigation number 33 can be explained by the application of fertilizers during

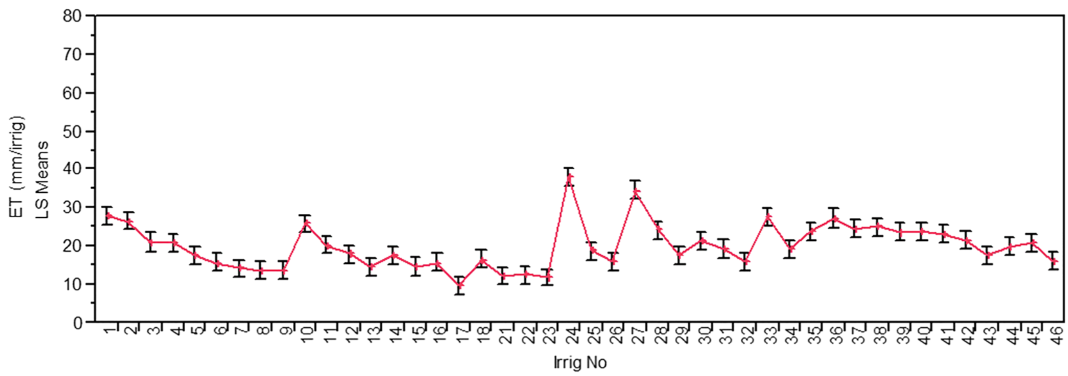

Figure 4. Effects of irrigation number on crop ET (mm per irrigation) [Colour figure can be viewed at wileyonlinelibrary.com]

irrigation number 32 and the additional irrigation given to the low EC treatments from irrigation number 35 onwards. Table IV also indicates that the effect of irrigation number on ET was highly significant, as expected, for the interaction between irrigation number and salinity. On the other hand, the interaction between irrigation number and ALA was not significant. This may be attributed to the fact that salinity effects on ET have masked the repairing capacity of ALA on ET.

3.2. Applied water

Since we could not obtain irrigation water flow meters that can withstand the high salinity levels, we relied on application time and calibration to calculate the amount of applied water for each tree. The study of the resulting volumes of water applied suggested that statistical analysis is required to provide more depth to the analysis of ET and IE. The analysis of applied water revealed significant differences where ALA treatments have received less water (about 42 l per tree per irrigation), compared with about 47 l per tree per irrigation for 0ALA treatments. Although this difference was not planned for during the experiment, it explained the effect of ALA treatments using more ET from less applied water compared with no ALA treatments, although more applied water practically means better leaching of salts for the EC treatments. As expected, the low EC treatments had received significantly more water (about 68 l per tree per irrigation) compared with high and medium EC treatments (33.5 and 31 l per tree per irrigation) respectively. In addition, the interaction between water applied and EC treatments was highly significant. Figure 5 shows the total applied water (mm) for each treatment by the end of the experiment (446 days).

3.3. Actual water use (ET)

Actual water use has to be interpreted with four factors in mind. They are the cumulative effect of salt with time in two EC treatments out of three, the effect of leaching during rainfall or heavy irrigation, the effect of ALA application and the temporal distribution of ET_0 as dictated by the prevailing weather conditions. It is important to emphasize that our irrigation strategy took advantage of the Diviner daily

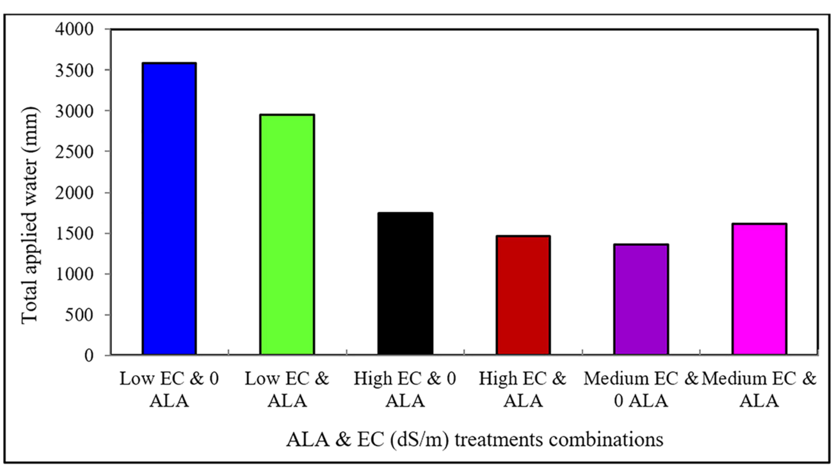

Figure 5. Total applied irrigation water for treatment combinations (mm) [Colour figure can be viewed at wileyonlinelibrary.com]

readings. As there was no intention to reduce EC effects by leaching, the nature of water use dictated by the weather evaporative demands and altered only by salinity and ALA was observed via the daily moisture depletion displayed by the Diviner meter. Figure 6 shows an example of the linear and non-linear water use trends indicated by the soil moisture depletion curve viewed directly in the screen of the Diviner meter. The data were transferred to Excel and plotted against time, adding two regression equations and their fitting lines. It is clear that the first 5 days of irrigation showed linear depletion, while the last 3 days clearly indicated the start of moisture limitation for ET as indicated by change in the slope. This was further confirmed by the high R^2 for linear and polynomial curve fittings on the first segment and the whole curve respectively. Such depletion patterns were plotted for all the irrigation cycles and various treatments. Interpretation of those depletion curves will be used in another paper discussing crop water requirements and irrigation intervals.

The statistical analysis showed that actual ET was significantly affected by irrigation number, ALA application and irrigation water salinity (Table IV). In addition, the interactions between ALA and salinity, irrigation number and salinity were also significant, while the other interactions were not significant at the 5% level. Figure 7 shows the results of means separation at the 5% level for the interaction between EC and ALA. Examining Figure 5 in conjunction with Figure 7, the reduction of about 17.5% in total applied water under low EC with ALA compared with low EC without ALA has resulted in 7.8% increase in actual average ET. This leads to higher irrigation efficiency (IE). The highest IE was 62.7%, obtained under low EC and ALA application, followed by 47.7% for low EC without ALA. As increased salinities have drastically reduced water use, the IE under high EC and ALA application was 35.5% compared with 31.4 for the same but without ALA. Medium EC treatments with and without ALA have resulted in 20.9 and 19.8% IE respectively. The reason for lower water use and lower IE under medium EC treatments compared with high EC needs further research and experimentation. However, in terms of irrigation water quality and infiltration rate, it is known that higher irrigation water EC is preferred when sodium adsorption ratio (SAR) is high (Rhoades, 1972; Oster and Schroer, 1979). Since the water source used in this experiment is the same (i.e. the same concentration of Ca and Mg), while the medium and high EC levels were generated using sodium chloride, it is envisaged that SAR will be very high for the salinity treatments. This may have impaired the infiltration process, and hence the leaching of the salts from the effective rooting depth which may in turn have reduced the amount of water used by the high SAR and medium EC compared with the high SAR and high EC. Furthermore, the high EC treatments received more irrigation water (about 226 l in total) compared with the medium EC treatment.

The maximum daily ET during the 44 irrigation cycles under low water EC were similar (8.11 and 8.13 mm with and without ALA respectively) obtained in the month of July 2017. This was similar to the 8.23 mm day^{-1} obtained in July by Dewidar *et al.* (2015) in a lysimeter-based water requirement study in Saudi Arabia. The average summer daily ET values for the months of May–September 2017 were 6.31 and 6.19 mm day^{-1} under low EC with and without ALA respectively. These values dropped to 0.52 and 0.51 under medium EC, 1.04 and 1.13 mm day^{-1} under high EC with and without ALA respectively, indicating the drastic effect of EC on crop ET.

Total ET during the 44 irrigation cycles measured were about 1850, 1710, 338, 269, 522 and 549 mm for low, medium and high EC irrigation water with and without ALA respectively. The seasonal average ET obtained under ALA and low EC water between August 2016 and August 2017 was 5.0 and 4.7 mm day^{-1} with and without ALA, close to those presented by the Dewidar *et al.* (2015) study

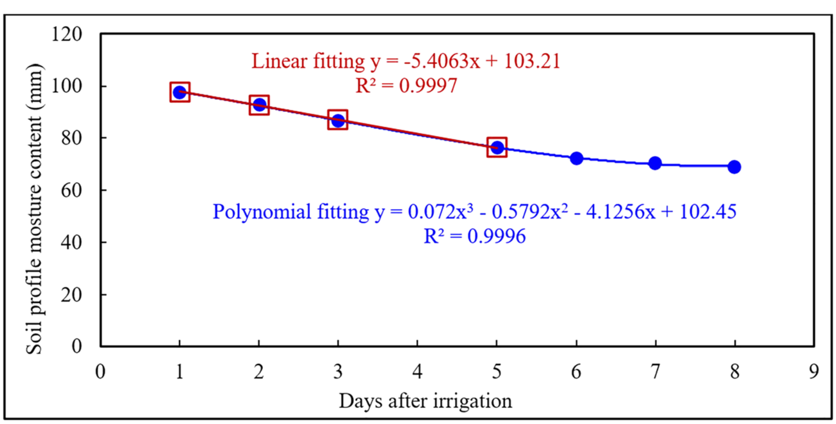

Figure 6. Example of polynomial and linear soil moisture depletion patterns [Colour figure can be viewed at wileyonlinelibrary.com]

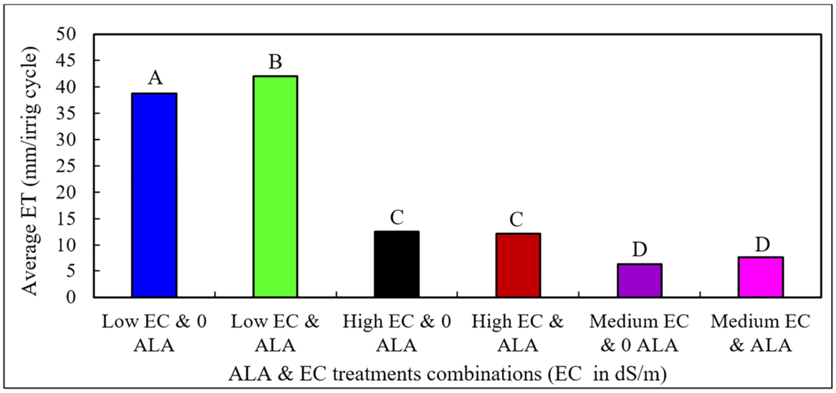

Figure 7. Mean actual water use (ET mm per irrigation cycle) for the interaction between EC and ALA. Means followed by the same letters are not significantly different at the 5% level [Colour figure can be viewed at wileyonlinelibrary.com]

although their date palm trees were 8 years old. Alamoud *et al*. (2012) obtained 2499 (mm yr^{-1}) for field-mature date palm trees in the Hofuf region of Saudi Arabia, some 177 km south-west of the Bahrain experimental site.

Temporal effects on ET together with the reference crop evapotranspiration are shown in Figure 8. This figure shows that in the first 10 irrigations, all the treatments showed water use below ET_0 since all were receiving the same water application time and did not show any upward inclination in the respective moisture depletion lines. There was a decreasing trend in ET for all treatments indicated by a similar general trend in ET_0 but more drastic for EC treatments due to the effects of salt accumulation. The rise in ET from irrigation number 10 (23 August–1 September) marked ALA application and the increase of irrigation time application for the low EC treatments. It is also clear in this period that ET for low EC treatments was comparable with ET_0. As can be seen from Figure 7, ET was not calculated during irrigation cycles 19 and 20 (24 November–29 December 2016) due to malfunction of the rain gauge. Irrigation cycles 24 and 27 (1–21 February and 15–28 March 2017) showed two peaks of ET for the medium and high EC treatments, which can be explained by the leaching of salts and the trees regaining normal ET from rainwater. This effect diminished when EC treatments continued with the medium and high salt concentrations. Thereafter, ET is seen in Figure 8 to steadily decline for the medium and high EC treatments irrespective of the changes in ET_0 compared with the low EC treatments that had exceeded ET_0 as the weather started to get hotter during the summer of 2017. This was attributed to salt accumulation in the root zone. Analysis of soil samples (not shown here) for EC and SAR at 30 cm depth before the experiment (22 May 2016), on 1 November 2016 and 1 March 2017, supported this finding.

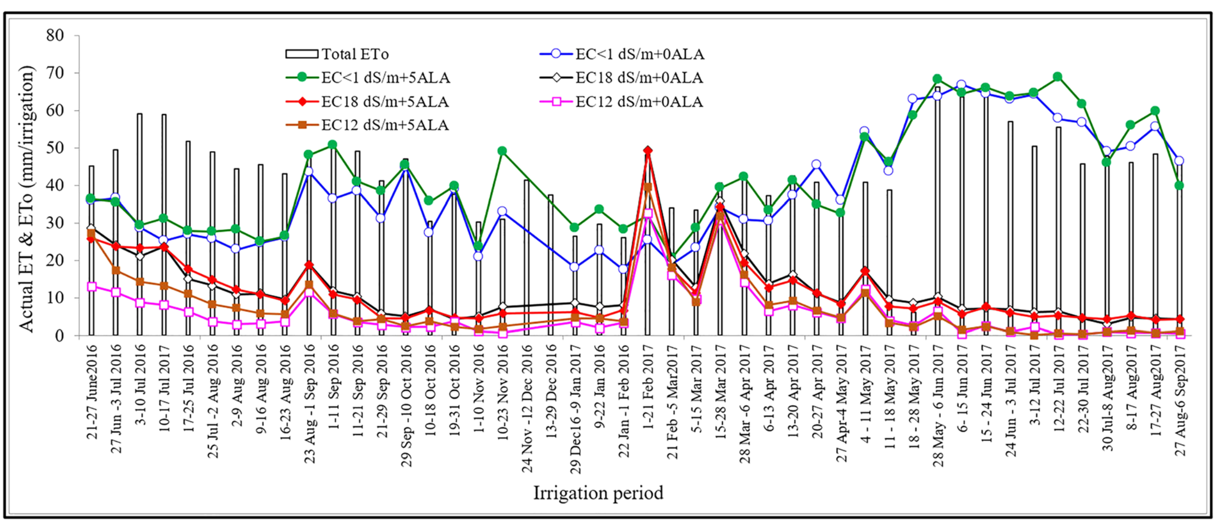

Figure 8. Temporal distribution of actual ET of the treatments' combinations (lines) and the reference crop evapotranspiration ET_0 (columns) for the period June 2016–September 2017

3.4. Effects of ALA

ALA was applied in 30 irrigation cycles out of the total of 46 cycles, which included the second irrigation cycle and the cycles from the 11th to the 35th and in the last three cycles (43–46). This was due to the procedure related to provision of 5-ALA in Bahrain. The overall effects of ALA application indicated significant differences in ET compared with no ALA application at $p < 0.0001$. Generally, ALA application has increased ET by about 7%. The interaction between ALA and irrigation water EC was highly significant at $p < 0.0001$. The application of ALA under low water salinity has resulted in significantly higher ET (42.1 mm per irrigation cycle) compared with 38.8 under no ALA application and same water salinity. On the other hand, ET under low water salinity has significantly exceeded the medium and high EC treatments apart from ALA application (Figure 7). Figure 7 also indicates that EC has the greatest effect on ET compared with ALA (see the difference between the two columns of low EC and the other columns of medium and high EC).

It is widely known that ALA application improves chlorophyll content. Table V shows the results of chlorophyll *a* and *b* and carotenoid content analysis at two dates of leaf sampling. It is clear from Table V that ALA significantly improved chlorophyll *a* and carotenoid at the first sampling date. The differences were not significant at the second sampling date, although chlorophyll *a* and *b* and carotenoid values were higher under ALA compared with no ALA treated trees. It is worth mentioning here that chlorophyll extraction from date palm leaves represents a challenge especially when a large number of samples are involved. This may be attributed to the fact that date palm leaves are thick and have a high lignin content. Moreover, there are clear seasonal differences in mineral contents of leaves of the same age and between leaves of young and old age, as indicated by Osman *et al.* (2010) and Al-Kahtani *et al.* (1986). This may probably lead to the supposition that chlorophyll contents may also vary with the growing season as a result of different assimilation rates and utilization of stored minerals during flowering and fruiting. This may explain the lower chlorophyll contents in the second samples of January 2017 and the variations that reduced the precision of detecting significant differences. Our analysis also revealed significant differences in chlorophyll *a* content between old and young leaves (not shown here) irrespective of ALA application. It is worth mentioning here that two out of the three ALA treated trees under low EC treatment flowered for the first time in July 2017, while no trees under EC stress flowered although some of them had flowered the year before.

3.5. Effects of irrigation water EC on crop ET

This was clear and highly significant at $p < 0.0001$. The reduction in ET reached 69.7 and 82.7% for high and medium EC treatments respectively, compared with the low EC irrigation water treatment. Most recently, Al-Muaini *et al.* (2019) reported a 68% reduction in ET of mature date palm trees in the UAE when irrigation water EC was increased from 5 to 15 dS m^{-1}. However, their experiment involved 25% as a factor of safety against reticulation inefficiencies and another 25% for leaching of salts. The average water use per irrigation cycle was about 40.5 mm under low EC compared with 12.3 and 7.0 mm under high and medium EC treatments respectively. Despite this high salinity of irrigation water, the high and medium EC watered date palm trees did not show severe stress signs apart from the pale colour of leaves by the end of the year. This might be due to the rainy days that prevailed during November and December 2016 and February and March 2017 and the ability of date palm trees to withstand high salinity levels. After calibration of the rain gauge, the total recorded rainfall of March 2017 reached 34.6 mm. Such rainfall during winter, when reference evapotranspiration (ET_0) is at its minimum value, combined with the loamy sand or sandy soils, may explain the ability of date palm to survive high irrigation water salinities during the rest of the year by leaching salts from the shallow root zone. This may also explain the tendency of farmers in the Arabian Peninsula to over-irrigate date palm trees especially when high EC groundwater is used for irrigation. Al-Muaini *et al.* (2019) reported the common practice of applying a flat rate of 275 l day^{-1} to mature date palm trees in the UAE. To understand the importance of rainfall in salt leaching, the drainage water was analysed for EC. Table VI shows the results of drainage water EC values with dates, lysimeter number and treatments. The concentration of salt in the leachate indicates the high

Table V. Effect of ALA application on chlorophyll *a*, *b* and carotenoid contents of date palm leaves. Vertical means having the same letters are not significantly different at 5% level

Treatments	Chlor. *a*	Chlor. *b*	Carotenoid	Chlor. *a*	Chlor. *b*	Carotenoid
	November 2016			January 2017		
ALA	1.02 A	0.54 A	0.38 A	0.84 A	0.34 A	0.33 A
0 ALA	0.86 B	0.44 A	0.32 B	0.74 A	0.30 A	0.30 A

Table VI. Salinity of drainage water (dS m^{-1}) by treatment, lysimeter number and date (NL; No Leachate)

Treatments	Lys No.	19 Oct. 2016	15 Feb. 2017	19 Feb. 2017	23 Feb 2017	28 Mar. 2017	29 Mar. 2017	3 Apr. 2017
ALA-EC < 1	14	NL	NL	NL	NL	NL	NL	NL
ALA-EC < 1	15	NL	NL	NL	NL	NL	NL	NL
ALA-EC < 1	22	NL	NL	16.3	NL	NL	NL	NL
0 ALA-EC < 1	13	NL	NL	0.0	NL	NL	NL	NL
0 ALA-EC < 1	23	NL	NL	0.0	NL	NL	NL	5.2
0 ALA-EC < 1	24	NL	NL	2.9	NL	NL	NL	NL
ALA-medium EC	1	51.4	NL	NL	NL	NL	NL	NL
ALA-medium EC	2	50.0	49.3	NL	NL	NL	NL	NL
ALA-medium EC	12	50.6	49.5	36.5	35.0	NL	NL	NL
0 ALA-medium EC	9	42.4	NL	NL	NL	NL	NL	NL
0 ALA-medium EC	10	43.7	NL	NL	NL	NL	NL	NL
0 ALA-medium EC	11	46.9	41.1	NL	NL	34.0	26.2	NL
ALA-high EC	6	53.5	51.0	NL	NL	NL	37.9	NL
ALA-high EC	7	49.6	NL	40.0	NL	NL	31.0	NL
ALA-high EC	8	53.7	NL	44.5	NL	NL	NL	NL
0 ALA-high EC	3	50.0	NL	NL	NL	NL	NL	NL
0 ALA-high EC	5	47.0	41.4	NL	NL	22.5	NL	NL
0 ALA-high EC	4	NL	NL	NL	NL	NL	NL	NL

potential of leaching practices whenever no soil-impeding layer is available beneath the surface. Therefore carefully designed drainage systems in date palm fields that are suffering from high water salinities may greatly improve water uptake, yield potential and contribute to the sustainability of date palm production in the Arabian Peninsula.

3.6. *Conclusions and recommendations*

It may be concluded that ALA application has significantly increased actual young date palm water use under low EC of irrigation water by about 7% and consequently improved irrigation efficiency from about 48% without ALA to 63%. Such improvement may be attributed to improved photosynthesis as a result of improved chlorophyll *a*. Irrigation water salinities between 15 and 20 dS m^{-1} drastically reduced ET by about 70–83% compared with low EC irrigation water under no leaching irrigation practices. Irrigation water salinities from 15 dS m^{-1} and above appeared to mask the effect of ALA on water use. However, the overall irrigation efficiency of ALA-treated trees was higher than untreated ones. Thus, economic analysis of different rates of ALA, together with water savings, environmental benefits and sustainability of irrigation, must be further investigated. It is important to mention here that the medium and high EC treatments used in this research were between 15 and 20 dS m^{-1}, thus care must be taken when referring to those salinity levels as medium and high for other crops. Rainfall in the peninsula, although meagre and erratic, can greatly help date palm trees recover normal ET rates but only for short periods. Date palm ET varies considerably during the season and with salinity, thus irrigation water application must be carefully designed to satisfy the evaporative demand and the leaching requirements for sustainable production and potential water savings. The balance between leaching requirements and over-irrigation must be carefully attained through careful irrigation system design.

It is recommended that research projects concerning water salinity and date palm trees be carried out for a prolonged period, pertaining to the tolerance and slow growth habit of date palm trees and the need to assess prolonged salt accumulation and leaching practices.

ACKNOWLEDGEMENTS

This research was funded by the Arabian Gulf University (AGU) under Project 'STS NRE 001 2015' at the Sultan Qaboos Centre for Desert Farming Techniques and Soilless Agriculture. The cooperation received from the higher AGU Administration, the Research Approval Committee and the AGU staff in the financial and purchasing departments is gratefully acknowledged. Special thanks to field assistant worker Mr. Abdalla Alsheikh, Drs Arnaud Lacheret and Noureddine Ben Khalaf for the French translation of the abstract. The provision of 5-ALA by Dr. Riyadh N. Rehani, SBI PHARMA and Neopharma regarding their contribution to make this publication accessible to the broader scientific community is highly acknowledged.

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