Al-Azhar Journal of Agricultural Engineering 8 (2025) 56

Contents lists available at Egyptian knowledge Bank (EKB)

Al-Azhar Journal of Agricultural Engineering

journal homepage: https://azeng.journals.ekb.eg/

Full length article

Using different irrigation systems to reduce water consumption in date palm trees under Toshka conditions

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ARTICLE INFO

Handling Editor - Dr. Mostafa H. Fayed

Keywords:

Irrigation water levels
Clay rates
Date palms
Water use efficiency
Irrigation water use efficiency
Yield response factor

Water and Irrigation Systems Engineering

ABSTRACT

Date palms demonstrate exceptional resilience to water and temperature stress, which significantly affects both yield quantity and quality. Over two consecutive seasons (2022/2023 and 2023/2024), a study was conducted on a private farm in Toshka, Aswan Governorate, Egypt, to examine the impact of irrigation water stress (DI = 100 %, 80 %, and 60 %) and different clay (bentonite) application rates (BCR = 0, 20, and 40 kg palm^{-1}) under three irrigation systems: Oscop drip (OIS), micro-jet (MIS), and bubbler (BIS). The study evaluated crop quality parameters, marketable yield (MY), actual water consumption (ACW), water use efficiency (WUE), irrigation water use efficiency (IWUE), and the yield response factor (Ky) for date palm trees (*Phoenix dactylifera* L.). The results showed that the highest marketable yield and most quality parameters, except total soluble solids (TSS), were achieved under OIS with DI = 100 % and BCR = 40 kg palm^{-1} in both seasons. In contrast, the lowest ACW values—1123.47 mm in 1st season and 1121.12 mm in the second—were recorded under OIS with DI = 60 % and BCR = 40 kg palm^{-1}. The highest WUE and IWUE values, reaching 1.72 and 1.20 kg m^{-3} in the first season and 1.75 and 1.23 kg m^{-3} in 2nd season, were observed under OIS with DI = 80 % and BCR = 40 kg palm^{-1}. Additionally, the lowest Ky values, 0.11 and 0.14 for the first and second seasons, respectively, were obtained under these conditions. This study concludes that implementing OIS with DI = 80 % and BCR = 40 kg palm^{-1} can reduce irrigation water use by up to 44 % while enhancing marketable yield by 32 % compared to the control treatment (BIS, DI = 100 %, and BCR = 0 kg palm^{-1}).

1. Introduction

The date palm (*Phoenix dactylifera* L.) is one of the oldest cultivated crops, with a history stretching back thousands of years in the arid regions of the Middle East and North Africa. Its high nutritional and economic value has driven its cultivation to spread to other regions with favorable growing conditions. However, the future of date palm cultivation is threatened by challenges such as water scarcity, extreme heat, salinity, soil degradation, and various diseases and pests. Implementing effective management strategies, including modern irrigation techniques, selecting cultivars suited to local conditions, and enhancing soil water and nutrient retention, is crucial for sustaining and improving palm cultivation and productivity (Alotaibi et al., 2023).

Water and heat stress present significant challenges to the sustainability of agriculture in arid regions. Water scarcity, in particular, profoundly affects the growth and productivity of date palms in these areas. With water resources becoming progressively limited, gaining insights into the drought tolerance of various date palm cultivars is essential to optimize irrigation practices and promote sustainable agricultural development (Ali-Dinar et al., 2023). Amending sandy soils with clay enhances fertility by enriching the soil with essential macro- and micronutrients. This improvement becomes particularly significant when the proportion of bentonite

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https://doi.org/10.21608/AZENG.2025.354085.1027
Peer review under responsibility of Faculty of Agricultural Engineering, Al-Azhar University, Cairo, Egypt.
Received 19 October 2024; Received in revised form 14 November 2024; Accepted 15 November 2024
Available online 31 January 2025

Nomenclature

ACW	: Actual water consumption, mm.
BCR	: Clay (bentonite) application rate, kg palm^{-1}.
BIS	: Bubbler irrigation system.
D	: Diameter of date palm fruit, cm.
DI	: Irrigation water stress, %.
ET_c	: Crop evapotranspiration, mm day^{-1}.
ET_m	: ET_c without stress, mm season^{-1}.
ET_o	: Reference evapotranspiration, mm day^{-1}.
FW	: Fruit weight, g.
IS	: Irrigation systems.
IWUE	: Irrigation water use efficiency, kg m^{-3}.
Ky	: Yield response factor.
L	: Length of date palm fruit, cm.
MC	: Moisture content, %.
MIS	: Micro-jet irrigation system.
MY	: Marketable yield, Mg ha^{-1}.
OIS	: Oscop drip irrigation system.
P	: Total protein, %.
TS	: Total sugar, %.
TSS	: Total soluble solids, %.
WUE	: Water use efficiency, kg m^{-3}.
Y_m	: Maximum yield at DI 100 %, ton ha^{-1}.

in the sandy soil exceeds 5% (Karbout et al., 2015). Increasing the fertility of coarse sandy soil by adding clay (bentonite) is a promising procedure to raise biomass production and improve the cation exchange capacity of these poor soils concerning its fraction and economic implementation rates. Additionally, clay (bentonite) addition at economic rates will provide barley and cucumber plants with substantial amounts of irrigation water and chemical fertilizers (El-Demerdash et al., 2019; El-Dardiry and El-Hady, 2015).

Cultivating cucumbers with sandy soil injection treatment (CIR = 15 tons fed^{-1}, HAR = 4 kg fed^{-1}, and 2 doses) under an irrigation rate (IR) of 60 % and a mulch film rate (MFR) of 70 % results in saving approximately 40 % of the applied irrigation water and reducing total mineral fertilizer usage by around 30 %. This method also increases the marketable yield of summer cucumber fruits by about 27 % in the first season and 36 % in the second season compared to the control treatment (UIS, IR = 100 %, and MFR = 100 %). For date palm fruits, the highest growth parameters and marketable yield were achieved at IR = 100 %, followed by IR = 85 % and IR = 70 %, likely because IR = 100 % meets the crop's full water requirements, while the other irrigation levels fall short (El-Demerdash et al., 2019). Using the Oscop drip irrigation system with 50 gm polymer under 75 % of ET_a significantly enhanced both fruit quality and yield under desert conditions, while improving water use efficiency. Additionally, this system reduced the total acidity in the berry juice of Flame Seedless grapes under desert conditions (Rabeh et al., 2022).

The bubbler irrigation system (BIS) distributes water less efficiently, achieving approximately 62 % distribution compared to the 97 % distribution of drip irrigation systems when used for date palm irrigation. Consequently, BIS leads to a significant reduction in date palm productivity compared to drip irrigation systems. It is concluded that a drip irrigation system, with proper planning and management, can effectively meet the water requirements of large trees like date palms (Al-Amoud, 2008).

Traditional surface irrigation is the least efficient compared to deep drip irrigation systems. Under African conditions, deep drip irrigation more than doubled vine weight compared to surface drip irrigation and produced six times the vine weight of traditional surface irrigation. Root growth extended to 1.75 m with deep drip irrigation, 1 m with traditional surface irrigation, and only 0.60 m horizontally with surface drip irrigation (Bainbridge, 2006). A recent study on mature date palm trees found that subsurface drip irrigation (SSDI) increased yield productivity while reducing irrigation water use compared to surface drip irrigation (SDI). Additionally, water use efficiency for date palms improved significantly with SSDI (Al-Amoud and Al-Saud, 2011). In Saudi Arabia, the seasonal actual evapotranspiration for date palms is approximately 1644 mm (Kassem, 2007). The yield response factor (Ky), which measures a crop's sensitivity to water deficit at different growth stages, is a key tool in irrigation management (Steduto et al., 2012). Maximizing water use efficiency requires adopting advanced irrigation methods such as drip irrigation. With increasing water scarcity, continued innovation, research, and the integration of modern technologies are essential for sustainable water management in agriculture (Samia et al., 2022; Zahrani et al., 2011).This study aimed to examine the effect of applied irrigation water stress and varying additive rates of clay (bentonite) under different irrigation systems on growth quality parameters, marketable yield, actual water consumption, water use efficiency, irrigation water use efficiency, and the yield response factor.

2. Materials and methods

2.1. Experiments

A field experiment was conducted in Toshka, Aswan Governorate, Egypt (22° 31' 45'' N, 31° 49' 13'' E, 85 m a.s.l.) during the 2022/2023 and 2023/2024 growing seasons. The experiment followed a split-split plot design, with three date palm trees serving as replicates. The trees, aged 9 years, were planted 8.0 meters apart both within rows and between trees. Data collected were statistically analyzed using the Co-state software program, following the methodology of Snedecor and

Cochran (1989). Fig. 1 shows the Siwy variety of date palm trees (*Phoenix dactylifera* L.) irrigated under three levels of irrigation water stress (DI = 100 %, 80 %, and 60 %, based on crop evapotranspiration (ET_c) and three different rates of clay (bentonite) application (BCR = 0, 20, and 40 kg palm^{-1}) across three irrigation systems: Oscop drip (OIS), micro-jet (MIS), and bubbler (BIS). Soil management practices, including the application of chemical fertilizers, were conducted according to the recommendations of the Ministry of Agriculture and Land Reclamation.

The length (L) in cm, diameter (D) in cm, total protein (P) in %, total sugar (TS) in %, moisture content (MC) in %, total soluble solids (TSS), fruit weight (FW) in grams, and marketable yield (MY) in Mg ha^{-1} were measured for the date palm fruits. Furthermore, the actual water consumption (ACW) in mm, water use efficiency (WUE) in kg m^{-3}, irrigation water use efficiency (IWUE) in kg m^{-3}, and yield response factor (Ky) were calculated for all date palm tree plots under varying levels of irrigation water stress (DI) and clay (bentonite) application rates (BCR), across different irrigation systems (IS).

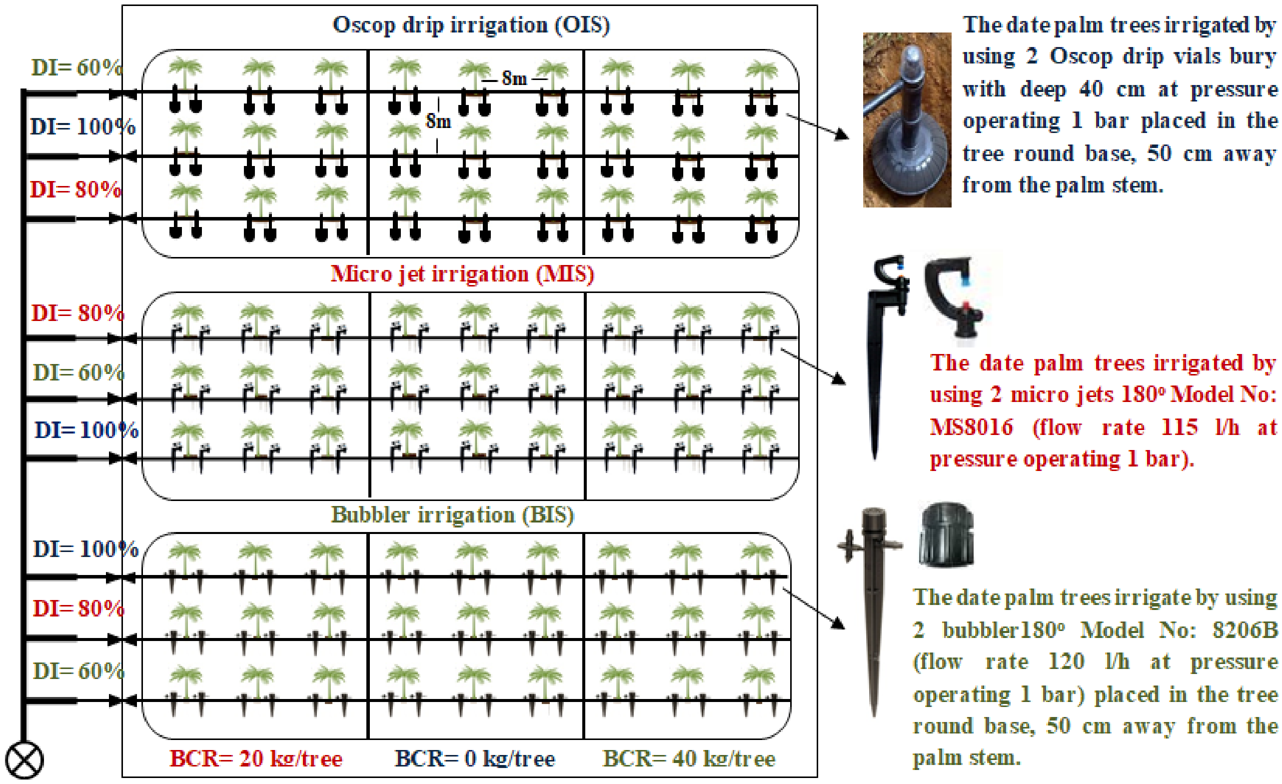


Fig.1. Field experiment layout in Toshka, Aswan governorate.

2.2. Clay (Bentonite) characteristics

The Bentonite clay sample used in this study was collected from a lightly exploited quarry located 15 km south of the Aswan city waterfall in Aswan province, Egypt. After being dried at 60°C for 48 hours, the sample was crushed using a jaw crusher to obtain particles smaller than 5 mm. Mineralogical analyses were conducted using X-ray diffraction (XRD), as shown in Fig. 2, which identified the clay minerals in the following order of abundance: Montmorillonite, Kaolinite, and Illite. Quartz and calcite were also present in small quantities as non-clay components. X-ray fluorescence (XRF) was employed to estimate the semi-quantitative percentages of the detected clay minerals across all fraction sizes in the sample. The results showed that the clay mineral composition consisted of 81 % Montmorillonite and 19 % Kaolinite. The physical and chemical properties of the Bentonite clay were analyzed according to the methods described by Klute (1986); Page et al. (1982); Holtz and Gibbs (1956), as detailed in Tables 1 and 2.

2.3. Soil characteristics

Soil samples were collected to analyze specific physical and chemical characteristics. The procedures followed the methods outlined by Klute (1986) for physical properties and Page et al. (1982) for chemical properties, as detailed in Tables 3 and 4.

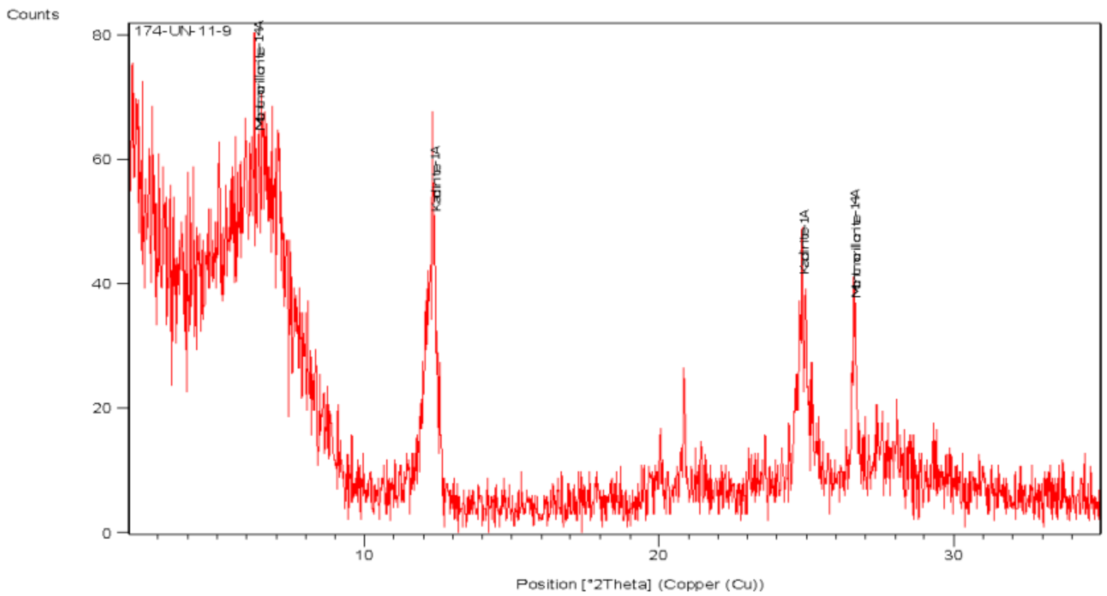


Fig. 2. X-ray diffractograms of the powder and treated calcic Bentonite clay fraction of sample.

Table 1

Physical characteristics of the clay (Bentonite) sample.

Particle size distribution (%)			ρb ($g\ cm^{-3}$)	FC (%)	WP (%)	AW (%)	FSI (%)
Sand	Silt	Clay					
7.02	14.23	78.75	0.51	48.19	16.67	31.52	115

Table 2

Chemical characteristics of the clay (Bentonite) sample.

EC ($dS\ m^{-1}$)	pH	CEC ($cmole\ kg^{-1}$)	Cations and anions of soluble salts, %							
			Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$CO3_3^{--}$	SO_4^{--}
0.69	7.57	96.72	0.49	0.21	3.86	2.34	0.68	2.15	-	4.07

Table 3

Some physical characteristics of experimental soil.

Soil depth (cm)	Particle size distribution (%)					Textural class	OM (%)	ρb ($g\ cm^{-3}$)	Ks ($cm\ h^{-1}$)	FC (%)	WP (%)	AW (%)
	C. sand	M. sand	F. sand	Silt	Clay							
0-20	5.21	23.09	59.43	5.56	6.71	Sandy	0.46	1.54	12.69	15.46	4.89	10.57
20-40	4.79	22.87	58.95	6.13	7.26	Sandy	0.41	1.56	12.94	14.98	4.67	10.31
40-60	4.23	22.56	58.47	6.91	7.83	Sandy	0.34	1.59	13.27	14.73	4.54	10.19
60-80	4.06	22.43	58.39	7.15	7.97	S	0.32	1.62	13.31	14.51	4.36	10.15

Table 4

Some chemical characteristics of experimental soil.

Soil depth (cm)	EC ($dS\ m^{-1}$)	pH	$CaCO_3$ %	CEC ($cmole\ kg^{-1}$)	Soluble ions ($meq\ l^{-1}$) in the saturated soil paste extract							
					Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$CO3_3^{--}$	SO_4^{--}
0-20	4.81	7.59	9.63	9.37	21.61	1.98	14.34	10.17	19.87	2.94	-	25.29
20-40	4.69	7.72	8.91	9.54	20.93	1.85	14.09	10.03	19.45	2.61	-	24.84
40-60	4.37	7.85	7.49	9.71	19.75	1.61	12.86	9.48	17.68	2.35	-	23.67
60-80	4.25	7.87	7.46	9.73	19.57	1.49	12.23	9.21	17.31	2.18	-	23.01

2.4. Irrigation water quality

Table 5 presents the evaluation of irrigation water quality, based on chemical analyses conducted following the methods outlined by Ayers and Westcot (1994).

2.5. Reference evapotranspiration (ET_o) and Crop evapotranspiration (ET_c)

The ET_o values shown in Table 6 were calculated using CropWat 8 software, applying the FAO Penman-Monteith equation, as described by Savva and Frenken (2002). Likewise, the ET_c values in Table 7 were determined using equation [1], as outlined by Savva and Frenken (2002).

$$ET_c = K_{c\,FAO} \times ET_o \quad ... [1]$$

where:

ET_c: crop evapotranspiration (mm day^{-1}),
$K_{c\,FAO}$: crop coefficient, and
ET_o: Reference evapotranspiration (mm day^{-1}).

2.6. Irrigation water stress (DI) applied throughout the growth stages

The amount of irrigation water stress (DI) applied to date palm trees, as presented in Table 8, was determined using the formula [2] provided by Keller and Karmeli (1974):

$$DI_{100,80,60\%} = (ET_c - pe)(K_r/E_a) + LR \quad ... [2]$$

where:

$DI_{100,80,60\%}$: Seasonal applied water irrigation stress (mm period^{-1}),
Pe: Effective rainfall (equal to zero mm season^{-1})
K_r: The correction factor for limited wetting at 70 % canopy coverage of carrots is Kr = 0.80 (Smith, 1992).
E_a: Irrigation efficiency for Oscop, micro jet and bubbler (85, 80 and 75 %) respectively (Allen et al. 1998), and

LR: Leaching requirements, at salinity levels of irrigation water, are calculated as 0.10 times ET_c (mm).

2.7. Actual consumption of water (ACW)

The actual consumptive water (ACW) was determined using equation [3] as described by Doorenbos and Pruitt (1984).

$$ACW = \frac{M_2 - M_1}{100} \times d_b \times d \quad ... [3]$$

where:

ACW: Actual consumption of water (mm),
M_1 and M_2: water content before and after irrigation respectively (%),
d_b: soil specific density, and
d: mean depth (mm).

2.8. Water use efficiency (WUE) and irrigation water use efficiency ($IWUE$)

WUE and IWUE were determined by the equations [4] and [5] (Howell et al., 2001, Michael, 1978):

$$WUE = \frac{MY}{ACW} \quad ... [4]$$

$$IWUE = \frac{MY}{DI} \quad ... [5]$$

where:

WUE and IWUE: Water use efficiency and irrigation water use efficiency (kg m^{-3}), and
MY: Marketable yield of date palm trees (kg ha^{-1}).

2.9. Yield response factor (Ky)

The Ky was calculated using equation [6] provided by Allen et al. (1998).

$$\left(1 - \frac{MY}{Y_m}\right) = K_y \times \left(1 - \frac{ACW}{ET_m}\right) \quad ... [6]$$

where

Y_m: Maximum yield at $DI_{100\,\%}$ (ton ha^{-1}),
K_y: Factor for yield response, and
ET_m: ET_c without stress (mm season^{-1}).

Table 5

Some chemical analysis for irrigation water.

Sample	pH	EC (dS m^{-1})	SAR	Soluble cations (meq l^{-1})				Soluble anions (meq l^{-1})			
				Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$CO3_3^{--}$	SO_4^{--}
Mean	7.89	1.97	3.65	7.61	3.39	4.94	3.76	4.68	7.45	-	7.57

Table 6

Calculated ET_o(mm day^{-1}) through date palm trees growth period.

Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
ET_o (mm day^{-1})	6.51	7.36	8.83	9.15	9.37	9.69	8.96	7.43	5.89	4.76	3.75	5.27

Table 7

Calculated ET_c (mm day^{-1}) through date palm trees growth period.

Stages	Initial	Development	Mid	Late	Seasonal
Planting date	1st Mar to 28th Jul	29th Jul to 1st Sep	2nd Sep to 29th Jan	30th Jan to 28th Feb	1st Mar to 28th Feb
Period length (day)	150	35	150	30	365
$K_{c\ FAO}$	0.80	0.90	1.00	0.80	-
ET_o (mm day^{-1})	1329.13	314.26	809.94	119.46	2572.79
$ET_{c\ 100\%}$ (mm)	1063.30	282.83	809.94	95.57	2251.64
Eff. Rainfall (mm)	0	0	0	0	0

Table 8

The applied irrigation water stress was calculated based on ET_c (mm day^{-1}) during the growth period of date palm trees.

IS	DI (%)	Applied Irrigation water stress (mm)				
		Growth Stages				
		Initial	Development	Mid	Late	Seasonal
OIS	100	1102.05	293.14	839.45	99.05	2333.69
	80	881.64	234.51	671.56	79.24	1866.95
	60	661.23	175.88	503.67	59.43	1400.21
MIS	100	1164.60	309.78	887.10	104.67	2466.15
	80	931.68	247.82	709.68	83.74	1972.92
	60	698.76	185.87	532.26	62.80	1479.69
BIS	100	1235.48	328.63	941.09	111.04	2616.24
	80	988.38	262.90	752.87	88.83	2092.98
	60	741.29	197.18	564.65	66.62	1569.74

3. Results and discussions

3.1. Impact of IS and DI under BCR treatments on the quality parameters of date palm fruits

The data in Figs. 3 and 4 indicate that the quality parameters of date palm fruits length (L) in cm, diameter (D) in cm, total protein (P) %, total sugar (TS) %, and moisture content (MC) % increase with higher applied irrigation water stress (DI) across all treatments, except for total soluble solids (TSS) %, which decrease as DI increases. Additionally, the data shows a significant advantage of the Oscop drip irrigation system (OIS) over the micro jet (MIS) and bubbler (BIS) irrigation systems for all treatments. The addition of clay (Bentonite) (BCR) to sandy soil also had a noticeable effect on all treatments. The results followed a similar trend for both the 2022/2023 and 2023/2024 seasons.

In the 1st season, the highest values for date palm fruit quality parameters (L, D, P, TS, and MC) were 4.28 cm, 2.63 cm, 2.38 %, 65.83 %, and 24.98 %, respectively. In the 2nd season, these values were 4.35 cm, 2.83 cm, 2.45 %, 73.41 %, and 26.07 %, respectively, under the OIS, DI = 100 %, and BCR = 40 kg $palm^{-1}$ treatment. In contrast, the lowest values for these parameters in the 1st season were 1.89 cm, 1.15 cm, 0.98 %, 20.45 %, and 10.83 %, and in the 2nd season, they were 1.93 cm, 1.28 cm, 1.03 %, 25.09 %, and 11.51 %, under the BIS, DI = 60 %, and BCR = 0 kg $palm^{-1}$ treatment. The TSS values for the OIS, DI = 100%, and BCR = 40 kg $palm^{-1}$ treatment were 36.42 % and 43.24 % for both seasons, while the TSS values for the BIS, DI = 60 %, and BCR = 0 kg $palm^{-1}$ treatment were 55.32 % and 67.17 %, respectively. These results align with those found by Rabeh et al. (2022); El-Demerdash et al. (2019); Karbout et al. (2015); Bainbridge (2006).

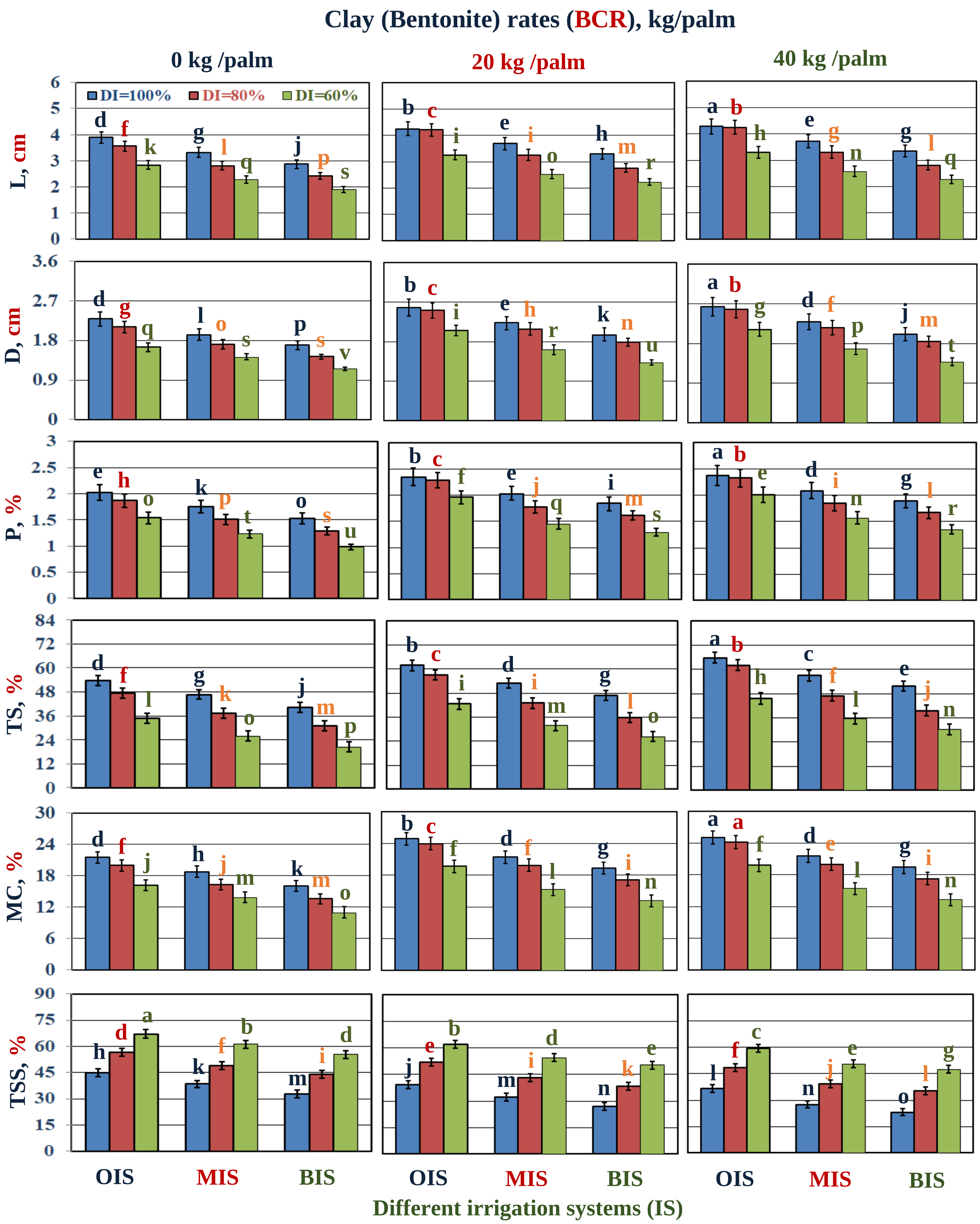


Fig. 3. Effect of applied water stress (DI, mm season^{-1}) on selected fruit quality parameters of date palms with varying clay (Bentonite) additive rates and different irrigation systems treatments during the 2022/2023 season.

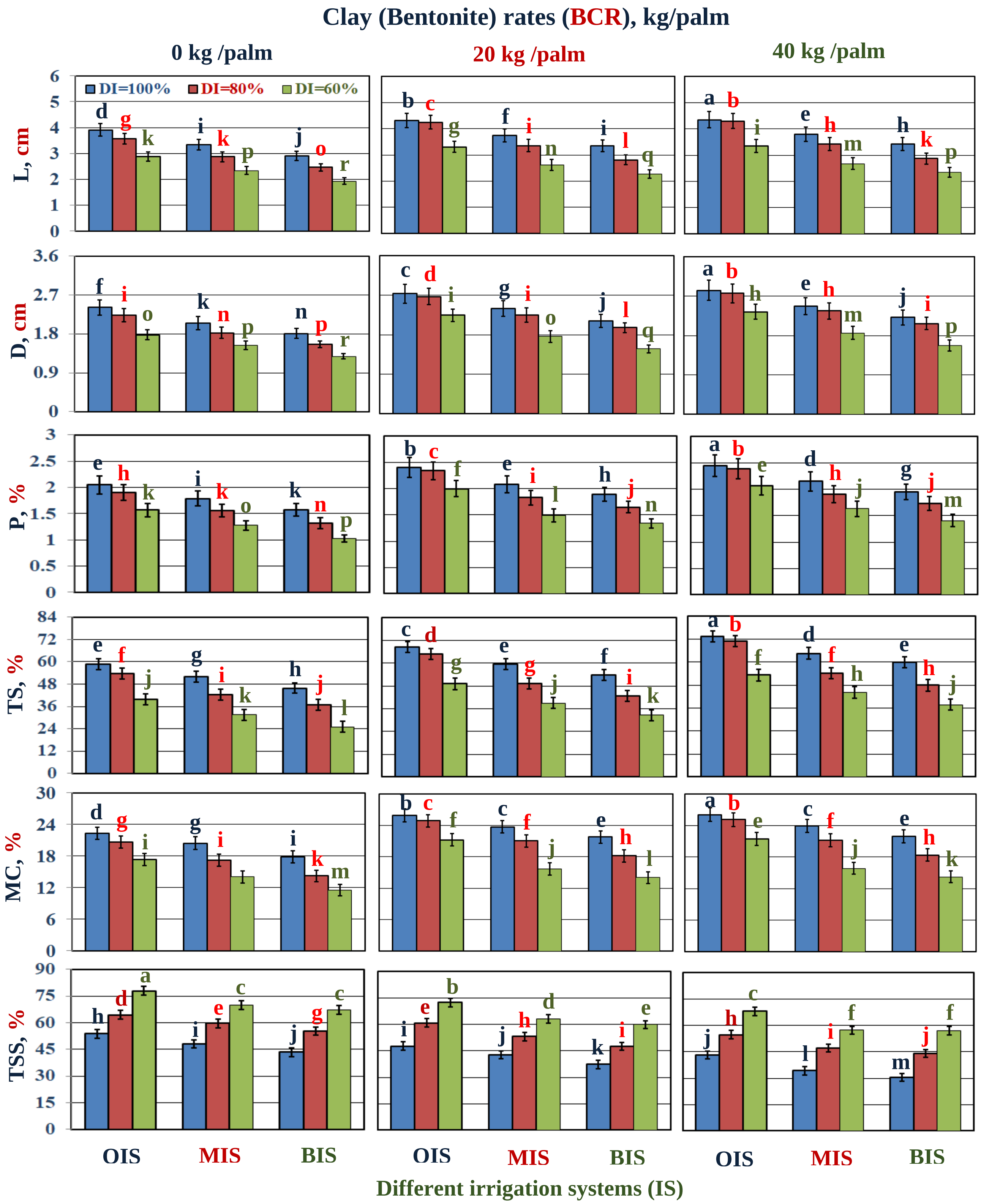


Fig. 4. Effect of applied water stress (DI, mm season^{-1}) on selected fruit quality parameters of date palms with varying clay (Bentonite) additive rates and different irrigation systems treatments during the 2023/2024 season.

3.2. Impact of IS and DI under BCR treatments on the yield production of date palm fruits

The data shown in Figs. 5 and 6 demonstrate that fruit weight (FW) in grams and marketable yield (MY) in Mg/ha for date palm fruits increase with higher DI across all treatments. Furthermore, the data reveal the significant advantage of the Oscop irrigation system (OIS) over the bubbler (BIS) and micro jet (MIS) systems for all treatments. The addition of BCR (Bentonite) to the sandy soil of date palm trees had a highly significant effect on all treatments. This trend was consistent across both the 2022/2023 and 2023/2024 seasons.

The highest values for FW and MY of date palm fruits were 14.83 g and 22.92 Mg ha^{-1}, respectively, in the 1st season, and 15.26 g and 23.47 Mg ha^{-1}, respectively, in the 2nd season under the OIS, DI = 100 %, and BCR = 40 kg palm^{-1} treatment. In contrast, the lowest values were 4.31 g and 6.41 Mg ha^{-1}, respectively, in the 1st season, and 4.74 g and 6.52 Mg ha^{-1}, respectively, in the 2nd season under the BIS, DI = 60 %, and BCR = 0 kg palm^{-1} treatment. These variations can be attributed to the improved physical, chemical, and water properties of the sandy soil due to the added clay (Bentonite), which increased soil moisture content in the effective root zone of the date palm trees. As a result, this allowed for better irrigation water retention and the addition of fertilizers, leading to higher productivity. Moreover, the Oscop drip irrigation system ensured more uniform water distribution in sandy soil compared to the other irrigation systems, contributing to increased marketable yield. These results are in line with the findings of Rabeh et al. (2022); El-Demerdash et al. (2019); Al-Amoud (2008).

3.3. Impact of IS and DI under BCR treatments on seasonal actual Consumptive water of date palm fruits

Data in Figs. 5 and 6 reveal that seasonal actual consumptive water (ACW) values (mm) for date palm fruits decrease as deficit irrigation (DI) levels are reduced across all treatments. Moreover, higher rates of clay (Bentonite) addition (BCR) to sandy soil further lower seasonal ACW values. The Oscop drip irrigation system (OIS), combined with increasing BCR rates, achieves the lowest seasonal ACW values compared to other treatments. This trend remained consistent throughout the 2022/2023 and 2023/2024 growing seasons.

The lowest seasonal ACW values were 1123.47 mm in the 1st season and 1121.12 mm in the 2nd season, observed under OIS with DI = 60 % and BCR = 40 kg palm^{-1} treatment. In contrast, the highest seasonal ACW values were 2325.12 mm in the 1st season and 2322.76 mm in the 2nd season under BIS with DI = 100 % and BCR = 0 kg palm^{-1} treatment.

These results can be explained by the improved water retention and storage capacity of sandy soil due to the addition of clay (Bentonite), which increases the available water and free swell index. This enhancement reduces the seasonal ACW by limiting water loss. Additionally, the OIS irrigation system ensures more uniform water distribution, reducing soil surface evaporation and further lowering seasonal ACW. Finally, applying irrigation water deficit stress reduces seasonal ETa values. These findings are consistent with those of Rabeh et al. (2022); El-Demerdash et al. (2019); Al-Amoud and Al-Saud (2011); Kassem (2007).

3.4. Impact of IS and DI under BCR treatments on WUE and IWUE of date palm fruits

Figs. 7 and 8 show that the highest WUE and IWUE for date palm fruits were 1.72 and 1.20 kg m^{-3}, and 1.75 and 1.23 kg m^{-3} for both seasons respectively, under the OIS, DI= 80 %, and BCR= 40 kg palm^{-1} treatment. In contrast, the lowest values were 0.43 and 0.41 kg/m^3, and 0.44 and 0.42 kg m^{-3} for both seasons respectively, under the BIS, DI= 60 %, and BCR= 0 kg palm^{-1} treatment.

Additionally, the WUE and IWUE values under the OIS, DI= 80 %, and BCR= 40 kg palm^{-1} treatment increased significantly by approximately 165 % and 108 %, and 161 % and 105 % for both seasons respectively, compared to the control treatment (BIS, DI = 100 %, and BCR = 0 kg palm^{-1} treatment). These results can be attributed to the addition of clay (Bentonite) to sandy soil, the use of the Oscop drip irrigation system, and water stress, which reduced surface soil evaporation. This, in turn, increased the storage capacity in the sandy soil, leading to higher marketable yields with lower water consumption. These findings align with those of Samia et al. (2022); El-Demerdash et al. (2019); Zahrani et al. (2011).

3.5. Impact of IS and DI under BCR treatments on date palm yield response factor (Ky)

The data in Fig. 7 show a clear linear relationship between the relative reduction in actual consumptive water $1-\left(\frac{ACW}{ET_{max}}\right)$ and the relative reduction in yield $1-\left(\frac{Y_a}{Y_{max}}\right)$ for date palm fruits. Strong positive correlations were found between these two variables for the 2022/2023 season under various BCR treatments: BCR = 0 kg palm^{-1} (r=0.872**,0.938**,0.955**), BCR = 20 kg palm^{-1} (r=0.798*,0.921**,0.947**) and BCR = 40 kg/palm (r=0.794*,0.921**,0.947**) for all irrigation systems (OIS, MIS, and BIS). Fig. 7 also shows that similar correlations were observed for the 2023/2024 season, with varying clay (Bentonite) addition rates (0, 20, and 40 kg/palm) across all irrigation systems (OIS, MIS, and BIS).

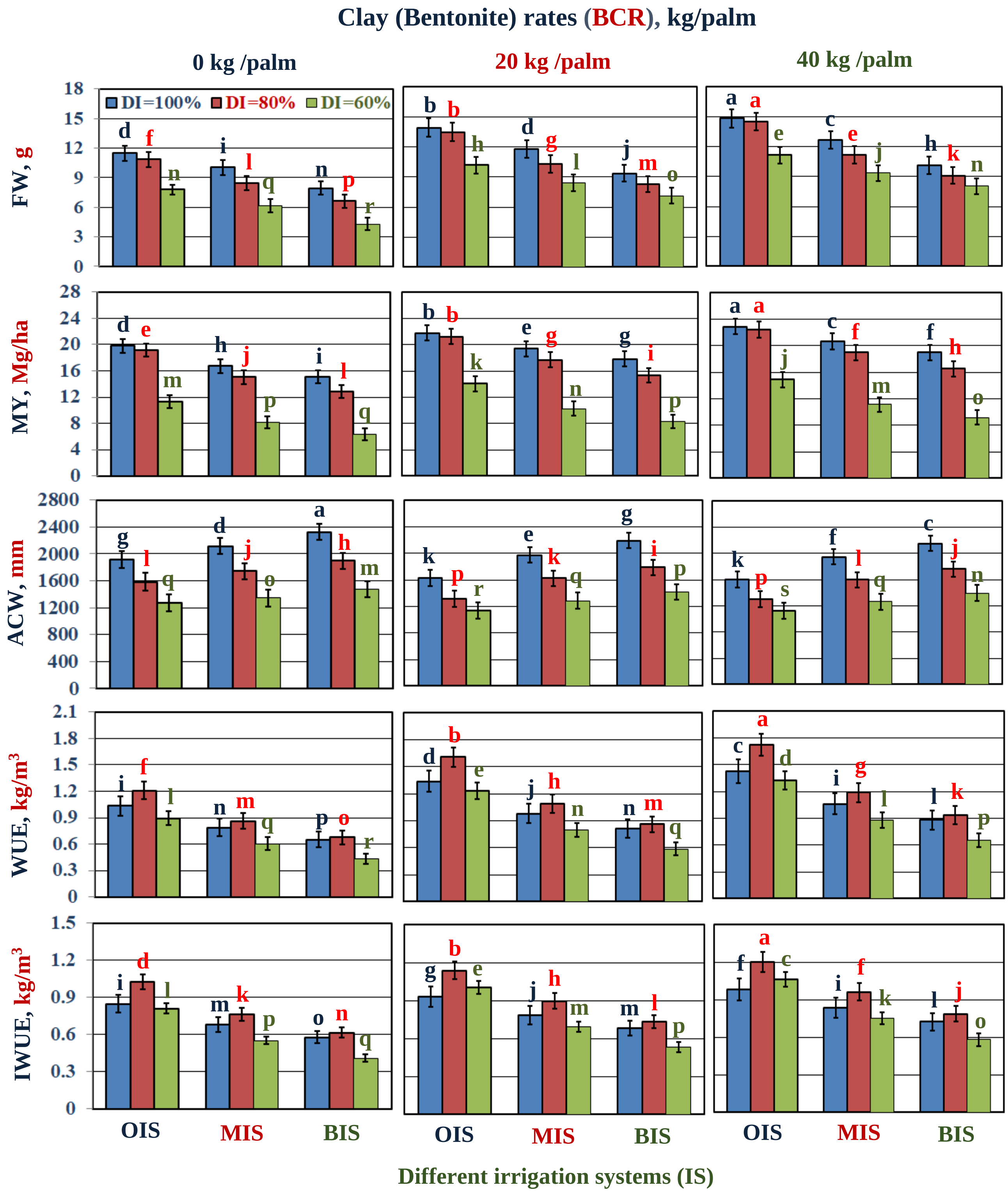


Fig. 5. Effect of applied water stress (DI, mm season^{-1}) on fruit weight (FW, g), marketable yield (MY, Mg ha^{-1}), seasonal actual consumption water (ACW, mm), water use efficiency (WUE, kg m^{-3}), and irrigation water use efficiency (IWUE, kg m^{-3}) of date palms with varying clay (Bentonite) additive rates and different irrigation systems treatments during the 2022/2023 season.

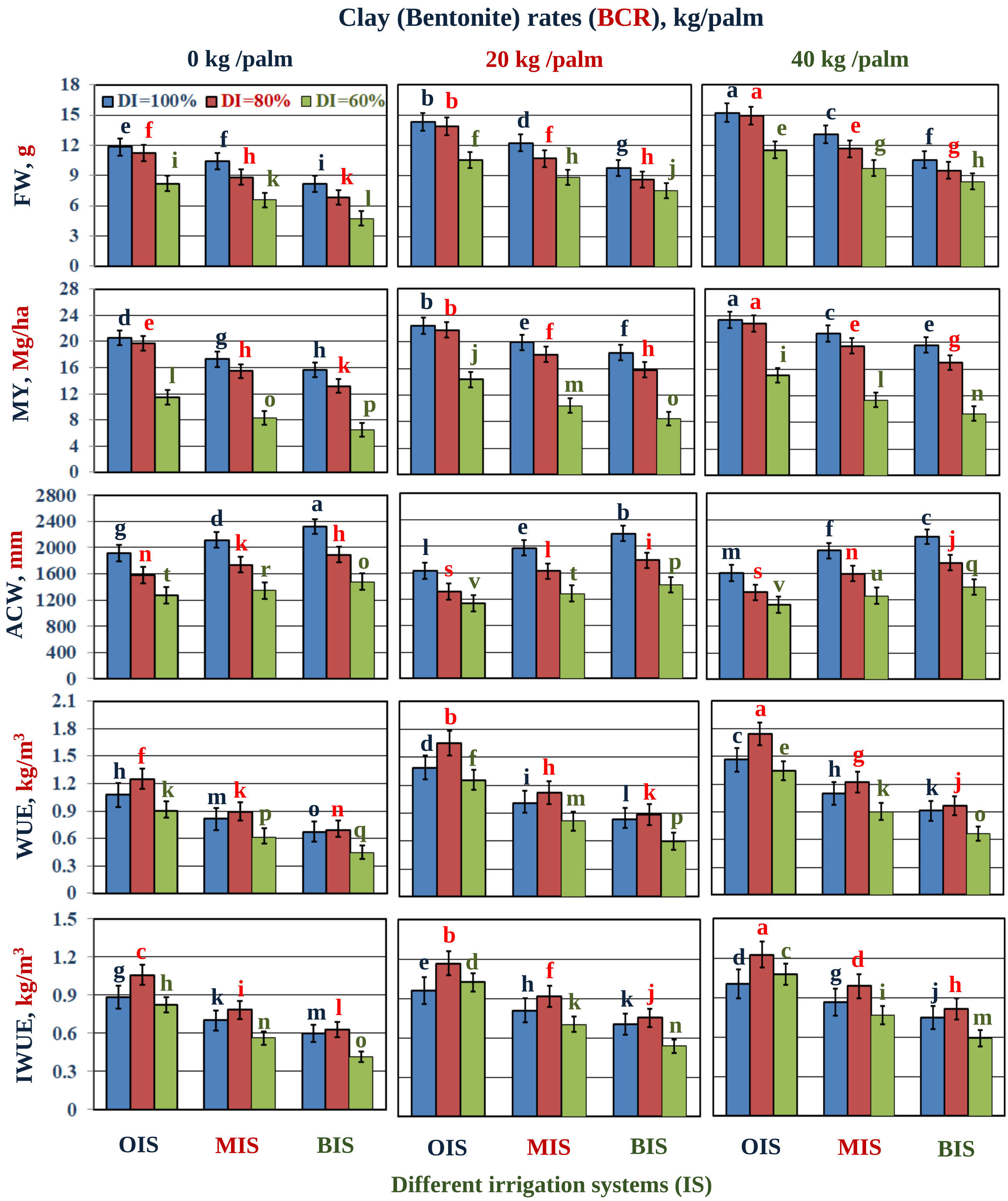
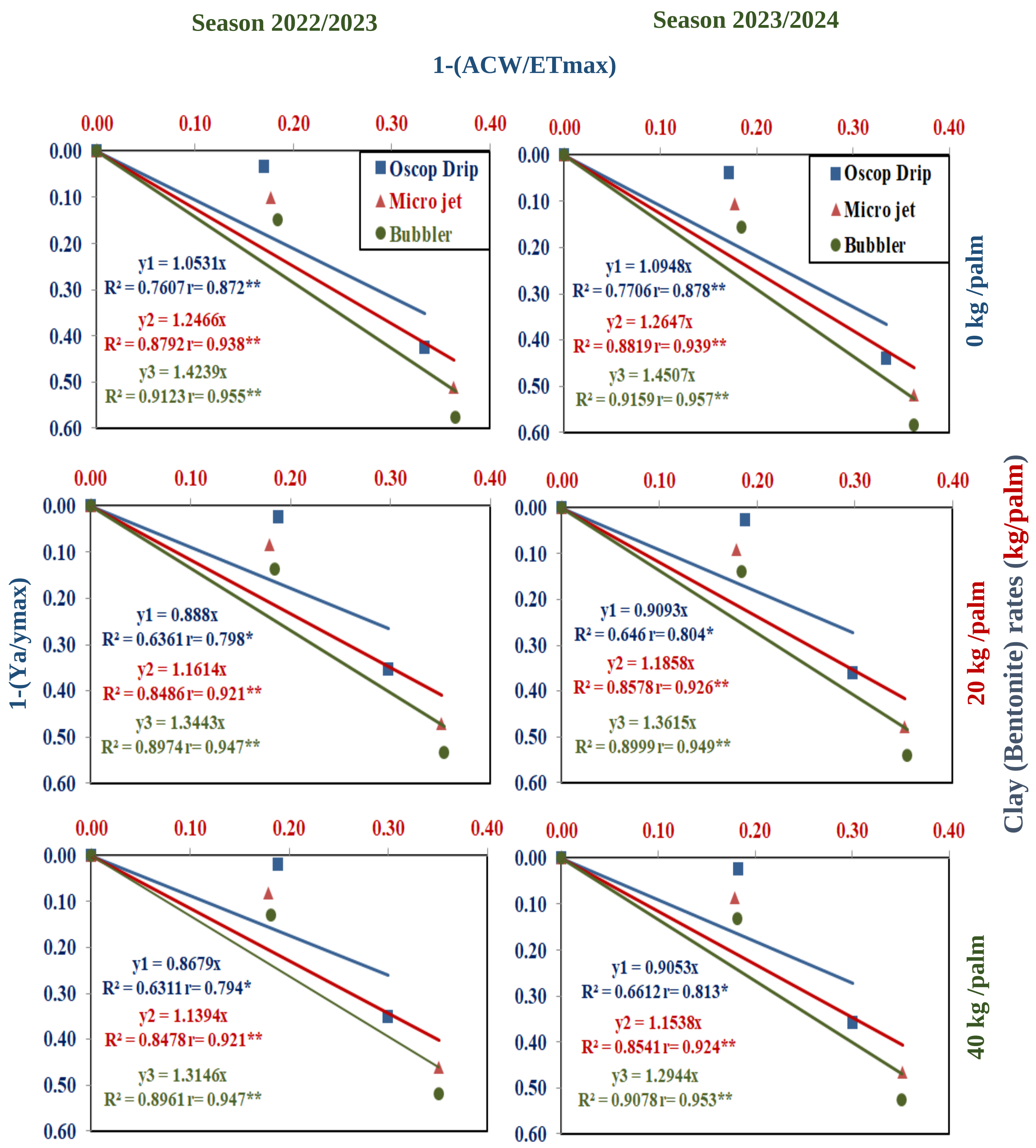


Fig. 6. Effect of applied water stress (DI, mm season^{-1}) on fruit weight (FW, g), marketable yield (MY, Mg ha^{-1}), actual consumption water (ACW, mm), water use efficiency (WUE, kg m^{-3}), and irrigation water use efficiency (IWUE, kg m^{-3}) of date palms with varying clay (Bentonite) additive rates and different irrigation systems treatments during the 2023/2024 season.



(Note: y1 at Oscop drip, y2 at Micro jet, and y3 at Bubbler)

Fig. 7. Relationship between the decrease in marketable yield (MY, Mg ha^{-1}) and actual consumption water (ACW, mm $season^{-1}$) for date palm trees with added clay (Bentonite) rates under different irrigation systems during the 2022/2023 and 2023/2024 seasons.

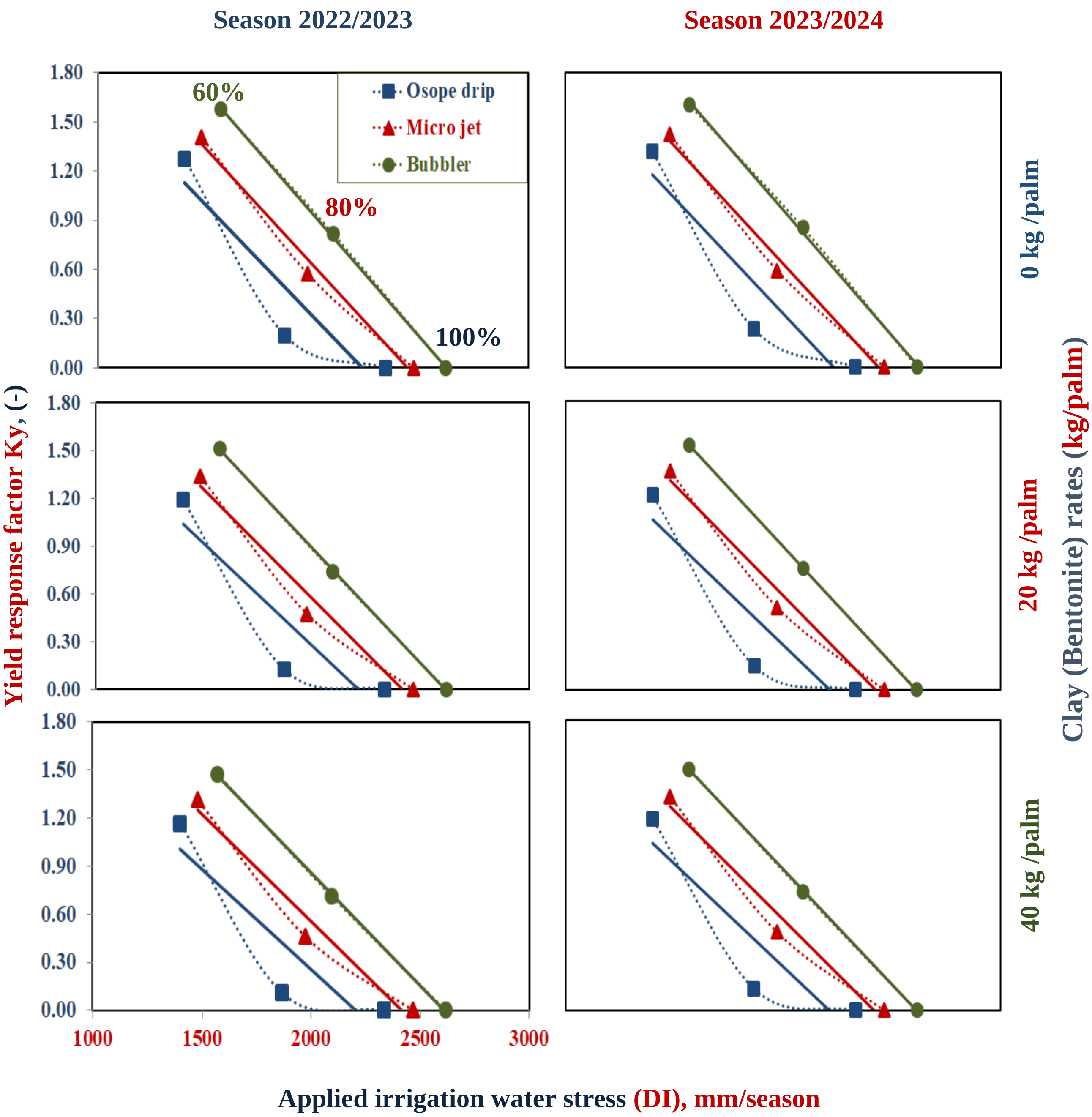


Fig. 8. Effect of irrigation water deficit levels (DI, mm season^{-1} on the yield response factor (Ky) of date palm under different clay (Bentonite) rates and irrigation system treatments for the 2022/2023 and 2023/2024 seasons.

Furthermore, Fig. 8 demonstrates that the Ky values for date palm fruits decrease as the applied irrigation water stress increases, regardless of the clay (Bentonite) addition rate or irrigation system used. The lowest Ky values were 0.11 and 0.14 for the 2022/2023 and 2023/2024 seasons, respectively, under the OIS, DI = 80 %, and BCR = 40 kg palm^{-1} treatment. In contrast, the highest Ky values were 1.58 and 1.60 for the 2022/2023 and 2023/2024 seasons, respectively, under the BIS, DI = 60 %, and BCR = 0 kg palm^{-1} treatment.

These results suggest that date palms have a high tolerance to water and temperature stress, with findings consistent with previous studies by El-Demerdash et al. (2019); Steduto et al. (2012).

4. Conclusions

This study highlighted the significant impact of applied irrigation water stress and varying rates of clay (bentonite) addition under different irrigation systems on the quality parameters, yield production, seasonal ET_a, IWUE, WUE, and Ky of date palm fruits in Toshka sandy soil. The results indicated that the highest values for growth parameters and marketable yield were obtained under the Oscop Irrigation System (OIS), with

100 % irrigation deficit (DI) and a BCR of 40 kg palm^{-1}. Conversely, the lowest seasonal ETa values were observed under OIS, DI = 60 %, and BCR = 40 kg palm^{-1}.

The minimum Ky values for date palm fruits were 0.11 and 0.14 for the 1st and 2nd seasons, respectively, under OIS, DI = 80 %, and BCR = 40 kg palm^{-1}treatment. Furthermore, WUE and IWUE values for date palm fruits showed a significant increase under OIS, DI = 80 %, and BCR = 40 kg palm^{-1}, with increases of around 165 % and 108 % in the 1st season, and 161 % and 105 % in the 2nd season, compared to the control treatment (BIS, DI = 100 %, and BCR = 0 kg palm^{-1}).

Based on these findings, it is recommended to implement OIS, DI = 80 %, and BCR = 40 kg palm^{-1} treatment for date palm cultivation under Toshka conditions. This approach can save approximately 44 % of the applied irrigation water while boosting marketable date palm fruit production by an average of 32 % across both seasons.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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استخدام أنظمة ري مختلفة لتقليل استهلاك المياه في أشجار نخيل البلح تحت ظروف توشكى

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الملخص العربي

يُعتبر نخيل التمر شديد التحمل للضغوط المائية والحرارية، مما يؤثر على كمية وجودة الإنتاج. أُجريت هذه التجربة خلال موسمين متتاليين في ٢٠٢٣/٢٠٢٢م و٢٠٢٤/٢٠٢٣م، في مزرعة خاصة بمنطقة توشكا، محافظة أسوان، مصر، لدراسة تأثير الضغط المائي المطبق(DI = 100, 80, 60%) ومعدلات إضافة الطين (البنتونيت) المختلفة (BCR = 0, 20, 40 kg/palm) تحت أنظمة ري مختلفة: الري بالتنقيط أوسكوب (OIS)، الري بالميكروجيت (MIS)، والري بالببلر (BIS) على معايير جودة المحصول، المحصول القابل للتسويق (MY)، المياه المستهلكة الفعلية (ACW)، كفاءة استخدام المياه (WUE)، كفاءة استخدام مياه الري (IWUE) ومعامل استجابة المحصول (Ky) لنخيل التمر (*Phoenix dactylifera* L.).

أظهرت النتائج أن المحصول القابل للتسويق ومعايير الجودة المدروسة باستثناء المواد الصلبة الذائبة الكلية (TSS) في ثمار نخيل التمر كانت الأعلى تحت نظام الري بالتنقيط أوسكوب (OIS)، DI = 100% و BCR = 40 kg/palm في كلا الموسمين. بينما كانت المياه المستهلكة الفعلية (ACW) بأقل القيم ١١٢٣,٤٧ و١١٢١,١٢ مم في الموسم الأول والثاني على التوالي، تحت نظام الري أوسكوب (OIS)، DI = 60% و BCR = 40 kg/palm. في نفس الوقت، كانت أعلى قيم لكفاءة استخدام المياه (WUE) وكفاءة استخدام مياه الري (IWUE) لنخيل التمر (١,٧٢ و١,٢٠ كجم/م٣) و (١,٧٥ و ١,٢٣ كجم/م٣) في الموسم الأول والثاني على التوالي، تحت نظام الري أوسكوب (OIS)، DI = 80% و BCR = 40 kg/palm. أخيرًا، كانت أقل قيم لمعامل استجابة المحصول (Ky) ٠,١١ و٠,١٤ في الموسم الأول والثاني على التوالي، تحت نظام الري أوسكوب (OIS)، DI = 80% و BCR = 40 kg/palm.

توصي هذه الدراسة بأن زراعة نخيل التمر تحت نظام الري أوسكوب (OIS)، DI = 80% و BCR = 40 kg/palm، يمكن أن يوفر حوالي ٤٤٪ من مياه الري المطبقة ويرتفع العائد القابل للتسويق لثمار نخيل التمر بنسبة ٣٢٪ كمعدل متوسط للموسمين مقارنة بالمعاملة المرجعية وهي (نظام BIS، DI = 100% و BCR = 0 kg/palm).