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Effect of Some Soil Conditioners on Water-Use Efficacy, Growth, and Yield of Date Palm Siwi Grown in Sandy Soil under Different Irrigation Regimes to Mitigate Climate Change

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Abstract: A field experiment was carried out at Al-Bahariya Oasis, Giza, Egypt, during three successive seasons to find out the effect of application of bentonite (BN) as a natural clay deposit at either 6 or 12 kg/palm tree and humic substances (HS) as organic amendment at either 0.75 or 1.0 L/palm tree incorporated with *Bacillus polymyxa* (BP) as a biofertilizers at 14 and 28 mL/L rates on growth, yield, and fruit weight of 10-year-old Siwi date palm cv. (*Phoenix dectylifera* L.). Siwi trees were cultivated in sandy texture soil at a distance of 8 × 8 m and were irrigated with 100%, 85%, and 70% of ET crop. Effects of the previous treatments on growth, date palm crop, soil properties, water relations, water-use efficiency (WUE), and economic return were also studied. The obtained results showed that the mean values of leaf length, leaflet length and width, fruit set%, bunch weight, yield/palm, yield/fed, fruit weight, flesh weight, and fruit pulp weight were increased in response to the different individual and combined treatments used in this study with various significance levels compared to the control treatment means in the studied three seasons. However, the superiority was for combining between amending the sandy soil with either low concentrations of BN (6 kg/tree) + HS (0.75 Liter/tree) + BP (14 mL/L) or high concentrations of BN (12 kg/tree) + HS (1.0 L/tree) + BP (28 mL/L) and irrigation with 85% of ETc water level, as such combinations attained the highest values in most of the mentioned values over both the sole and combined treatments in the studied three seasons. Furthermore, the results indicated that the highest monthly ETc values occurred during June and July months, while the lowest values occurred during December and January months. Additionally, water productivity (WP) increased considerably by reduction of water quantity (70% ETc) associated with soil conditioner treatment (BN.12 kg +HS 1 L + BP. 28 mL/L), and values were 2.17, 2.25, and 2.27 kg fruit/m^3 of water irrigation during the growing seasons, respectively. The highest net return was attributed to irrigation with 85% of ETc water level along with the application of soil conditioners at high rates. Accordingly, it is advisable to apply the soil conditioners of bentonite (at 6 or 12 kg/tree) and humic substances (at either 0.75 or 1.0 L/tree) with *B. polymyxa* (at either 14 or 28 mL/L) plus irrigation with either 85% or 70% of ETc water level to obtain the best growth, highest yield, (WP), and gross return from var. Siwi date palm grown under an oasis agro-system.

Keywords: date palm; Siwi cv.; *Phoenix dectylifera*; growth; yield; fruit weight; bentonite; *Bacillus polymyxa*; biofertilizers; irrigation water

Citation: Hassan, K.H.A.; Alamery, S.; El-Kholy, M.F.; Das, S.; Salem-Bekhit, M.M. Effect of Some Soil Conditioners on Water-Use Efficacy, Growth, and Yield of Date Palm Siwi Grown in Sandy Soil under Different Irrigation Regimes to Mitigate Climate Change. *Sustainability* **2022**, *14*, 11421. https://doi.org/10.3390/su141811421

Academic Editors: Marc A. Rosen and Teodor Rusu

Received: 31 May 2022
Accepted: 2 September 2022
Published: 12 September 2022

1. Introduction

Due to the pressing water-deficit problem in Egypt, especially after building the Grand Ethiopian Renaissance Dam (GERD), it has become urgent to identify economical crops that consume the least water and their efficient management, among which may be date palm varieties. Date palm (*Phoenix dactylifera* L.) is one of the most indispensable fruit trees in the world, especially in the arid and semi-arid regions. Egypt ranks as the first largest date producer among world countries, as its production is approximately 1.4 million tons. The Siwi date palm variety is the most significant semi-dry date in Egypt. It represents approximately 13.2% of the overall production. Date palm fruits are marketed worldwide as a highly nutritious and cheap fruit as well as high gross return fruits, achieving valuable profit for farmers and the country alike in the desert-like regions [1,2]. There is a common misconception among farmers that dates palm trees can tolerate drought and can be grown well with small amounts of water supplies. However, such beliefs are not correct because date palm trees actually need adequate amounts of water to promote growth through maintaining all metabolic processes in a vital and vigorous way [3]. The yearly water requirement needed for a mature date palm tree varies from 115–306 m^3 depending on the climate conditions, soil type, and date variety [4]. In Egypt, the amount of water required for irrigating the date palm tree ranges between 86–124 m^3/tree (10.28–14.88 m^3/100 m^2) [4]. In this regard, ref. [5] emphasized that date palm trees need sufficient water of convenient quality to reach full potential [6]. Date palm trees are drought-resistant plants, but when they are exposed to prolonged drought, they become stunted and cease to grow. On the other hand, ref. [7] cited that although the highest yield of date palm tree is achieved by irrigation with its full water requirements, it can also be attained by only 50% of water requirements or less in the presence of the proper soil conditioners.

Therefore, the application of soil amendments of various soil types is considered a crucial factor for the sustainability of oasis agro-systems [8]. In dry land and oasis, water is considered the most affecting factor for crop production and soil amendments, such as organic matter (OM), e.g., bentonite and bacillus bacterium, which is the key factor for preventing water loss. Apart from the supply of N, P, K and other nutrients, OM application increases water-holding capacity, cation exchange capacity (CEC), soil fertility, and sustainability of the agro-system over time. In this regard, ref. [9] indicated that application of plant refuse compost at 100 t/hm^2 increased soil-moisture retention and fertility. Likewise, ref. [10] reported that OM content of 4–5% in sandy soil where date palm trees grow can hold ten times the amount of water and nutrients compared to sandy soil with lower OM content. This in turn, would greatly support water-saving efforts and increase water-use efficiency. Regarding date palm varieties, similar observations were also detected [11,12].

Bentonite as a valuable absorbent swelling clay is widely used alone or with humates to increase the CEC and improve the fertility of sandy soil. This truth was documented by ref. [12] on Deglet Nour date palm trees, ref. [13] on sugarcane, ref. [14] on aloe vera, ref. [15] and on wheat and peanut as well.

Likewise, microbial inoculation with some effective microorganisms such as *Bacillus* spp. plant growth-promoting rhizobacteria (PGPR) may hasten date palm production in oasis agro-systems, as such bacteria do not only increase the plant growth, but they also improve nutritional assimilation of plants, suppress pathogens in the rhizosphere, fix the root-associated N, solubilize P_2O_5 compounds, produce plant growth-promoting substances, aggregate partial distribution, and improve soil porosity [16,17]. The above-mentioned benefits were demonstrated by ref. [16] on wheatgrass, ryegrass, and white clover, ref. [18] on wheat, ref. [19] on *Arabidopsis thaliana*, ref. [20] on sugar beet, ref. [17] and on wheat. Applying deficit irrigation to palm trees that are grown in dry areas can maximize water productivity [21]. The increase in yield might be linked to the availability of optimum soil moisture, which promotes balanced root growth and nutrient intake. Ref. [12] determined the effect of sandy soil (S) mixed with farm manure (M) and bentonite clay (B) BSM on the soil characteristics and date palm trees morphological characteristics.

Soil macro- and micronutrient contents were improved after BSM. Retention of soil water in BSM was also elevated compared to an untreated soil (no amendment). The improvement of morphological characteristics was observed for the canopy diameter in BSM treatment compared to untreated palm trees. Likewise, the leaf number increased, and height of the palm trees increased as well.

However, this work aims to improve the growth and yield of Siwi date palms cultivated and grown in sandy soil through organic, inorganic, and bio treatments under various irrigation water levels.

2. Materials and Methods

A field experiment was conducted in a private orchard at Al-Bahariya Oasis district, Giza, Egypt, at (28°19′10″ N: 28°57′35″ E. 130 m a.s.l.) during the three successive seasons of 2018/19, 2019/20, and 2020/21 with the aim to study the effect of bentonite, humic substances, and *Bacillus polymyxa* plant growth-promoting rhizobacteria PGPR in combinations on WP, growth, and productivity of Siwi date palm cv., bearing in mind that palm trees were grown in sandy soil and were irrigated with different levels of water.

Therefore, 27 mature date palm trees (*Phonex dactylifera* L.) var. Siwi of the same size and growth vigor (10 years old) were planted at a distance of 8 × 8 m. The layout of the experiment in the 3 studied seasons was split plot design with three replicates [22], where irrigation levels were devoted for the main plots, whereas soil amendments were devoted for the sub-plots. The treatments of both water levels and soil amendments were as follows:

2.1. Irrigation Treatments (Main Plots)

Irrigation treatments as a percentage of crops evapotranspiration (ETc%) were applied at the following 3 levels:

- I1 Irrigation with amount of water equals 100% of potential evapotranspiration (ETcrop).
- I2 Irrigation with amount of water equals 85% of potential evapotranspiration (ETcrop).
- I3 Irrigation with amount of water equals 70% of potential evapotranspiration (ETcrop).

2.2. Soil Conditioners Treatments (Sub-Plots)

A combination of bentonite BN (as natural swelling clay) + humic substance HS (as an organic amendment) + *Bacillus polymyxa* BP plant growth-promoting rhizobacteria PGPR (as liquid biofertilizers, 109 c.f.u.) was applied at the following rates for each palm tree:

A—Without soil conditioners (control);

B—BN (6 kg/tree) + HS (0.75 L/tree) + "*Bacillus polymyxa*" biofertilizers BP (109 c.f.u.) plant growth-promoting rhizobacteria (PGPR at 14 mL/L);

C—BN. (12 kg/tree) + HS (1.0 L/tree) + "*Bacillus polymyxa*" biofertilizers BP plant growth-promoting rhizobacteria PGPR (109 c.f.u.) at 28 mL/L.

2.3. Soil Analysis

Samples of soil were collected from the date palm rhizosphere zone at three different depths (0–30, 30–60, and 60–90 cm) and oven-dried at 55 °C, and their physical and chemical properties were determined using the methods described by [23,24]. The constant soil moisture was measured by the pressure membrane apparatus explained by [25]. The analysis results are summarized in Tables 1 and 2.

Table 1. Physical characteristics of the experimental soil.

Soil Depth (cm)	Particle Size Distribution %				Textural Class	Organic Matter (%)	Bulk Density g/cm^3	Field Capacity (%)	Wilting Point (%)	Available Water (%)
	Coarse Sand	Fine Sand	Silt	Clay						
0–30	28.48	61.70	5.27	4.55	Sandy soil	0.52	1.60	12.6	3.3	9.3
30–60	27.81	60.55	6.23	5.41		0.45	1.63	12.3	2.9	9.4
60–90	26.72	60.04	6.97	6.27		0.39	1.66	12.0	2.6	9.4

Table 2. Chemical characteristics of the experimental soil.

Soil Depth (cm)	EC (dS m^{-1})	pH	$CaCO_3$ %	Soluble Ions (meq/L) in Saturated Soil Paste Extract							
				Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	$CO_3^=$	$SO_4^=$
0–30	2.31	7.48	5.51	10.39	1.51	7.17	4.79	8.3	2.87	-	12.69
30–60	2.22	7.53	3.95	9.27	1.43	6.86	4.11	7.98	1.95	-	11.74
60–90	1.81	7.61	2.37	7.51	0.69	5.59	3.46	5.99	1.84	-	9.42

2.4. Irrigation Water Quality

The chemical analysis of irrigation water was evaluated according to the methods of [26] and is listed in Table 3.

Table 3. Chemical analysis of irrigation water.

Sample	pH	EC dS m^{-1}	SAR	Soluble Cations, meq/L				Soluble Anions, meq/L			
				Na^+	K^+	Ca^{++}	Mg^{++}	CL^-	HCO_3^-	$CO_3^=$	$SO_4^=$
Mean	7.93	0.46	1.95	2.02	0.57	0.77	1.36	2.29	1.74	-	0.69

The chemical analysis of bentonite and characteristics of humic substances were measured and are expressed in Tables 4 and 5, respectively.

Table 4. The chemical analysis of bentonite.

Bentonite Composition (on a Weight Basis)						
SiO_2	Al_2O_3	Na_2O	CaO	MgO	K_2O	Fe_2O_3
73.20%	11.40%	0.31%	2.67%	1.05%	2.58%	0.29%

Table 5. Characteristics of humic substances extracted from biogas manure.

Samples	Humic Acid (%)	Fulvic Acid (%)	Total (mmol/100 g HS)			Total Macro-Elements (%)		
			Acidity	Phenolic Groups	Carboxylic Groups	N	P	K
HS-B.	30.8	17.1	879	510	368	5.1	2.3	4.6

HS-B., humic substances extracted from biogas manure.

Regarding the above-mentioned substances, they were dark-yellow powder, and their pH was 7.22 and EC values were 2.95 dS·m^{-1}. The substances were obtained from El-Basatin Industrial Zone, Cairo, Egypt.

In addition, the average of the month's temperature °C, wind speed (m/s), solar radiation, relative humidity (%), and rain fall from the Metrological Authority of Giza governorate are outlined in Table 6.

Table 6. Meteorological data in 2018, 2019, and 2020 seasons.

Season	**2018**						**2019**						**2020**					
Month	**T.Max**	**T.min.**	**W.S**	**R.H**	**S.R**	**R.F**	**T.max**	**T.min**	**W.S**	**R.H**	**S.R**	**R.F**	**T.max**	**T.min**	**W.S**	**R.H**	**S.R**	**R.F**
January	19.4	10.3	2.6	60	385	1.1	17.1	4.4	3.0	48.2	353	1.5	16.5	5.0	3.3	63.9	343	6.5
February	21.5	8.0	2.0	62	461	5.1	19.4	6.2	2.9	46.6	416	1.83	18.9	6.7	2.8	61.3	403	109.2
March	25.4	12.0	2.3	50	569	10.3	22.8	8.4	3.4	40.4	522	0.44	22.3	8.7	3.2	55.0	502	8.4
April	28.8	15.8	2.4	41	590	5.5	27.9	12.7	3.3	32.7	571	0.22	26.6	11.5	2.9	45.0	598	0.0
May	34.6	19.4	2.0	34	627	0.0	35.6	18.7	3.3	22.0	602	0	33.1	16.7	3.4	32.7	611	0.0
June	36.7	16.0	2.0	23	650	0.0	37.2	22.1	3.6	29.0	620	0	36.1	19.8	3.4	28.3	625	0.6
July	38.2	24.5	1.6	42	645	0.0	38.1	22.9	3.4	30.3	650	0	36.8	21.4	3.4	30.8	650	0.0
August	37.1	24.6	2.0	46	636	0.0	37.5	22.5	3.1	31.4	595	0	37.4	22.0	3.3	33.1	577	0.0
September	34.9	22.3	2.9	46	545	0.0	34.3	20.0	3.4	40.8	485	0	36.5	21.3	3.5	37.4	567	0.0
October	31.0	18.5	1.9	47	495	4.8	31.9	18.1	2.8	41.1	478	1.46	31.7	18.0	3.3	45.2	476	0.7
November	25.5	13.7	1.7	54	399	26.0	26.8	13.3	2.3	45.6	387	0	23.1	12.1	2.7	60.1	370	7.4
December	23.9	12.4	2.3	64	289	34.8	19.6	7.9	3.1	62.8	329	20.4	21.2	9.7	2.7	58.8	317	1.0

T.max and T.min, maximum and minimum temperature °C; W.S, wind speed (m/s); S.R, solar radiation (Mg^2/cal/m); R.H, relative humidity (%); R.F, rainfall (mm/month). (Data were obtained from the agro-meteorological Unit at SWERI, ARC.)

2.5. Crop–Soil–Water Relations

2.5.1. Reference Crop Evapotranspiration (ETo)

Water requirements were evaluated by meteorological parameters using the "WATER" computer model [27], based on calculation using the Doorenbos and Pruitt equation and the Kc values (Table 6). Ref. [7] adapted the radiation formula to predict potential evapotranspiration as follows:

$$ETp = bwRs/L - 0.3 \quad (1)$$

where: ETp = daily potential evapotranspiration (mm/day); b = adjustment factor based on wind and mean relative humidity; W = weighting factor based on temperature and elevation above sea level; Rs = daily total incoming solar radiation for the period of consideration (cal/cm^2/day); L = latent heat of vaporization of water (cal/cm^2/day); and factors (b) and (w) could be obtained from the tables cited by [7].

2.5.2. Crop Evapotranspiration (ETc)

According to the following equation given by [28], the ETc values were calculated

$$ETc = ETo \times Kc \quad (2)$$

where ETc = crop evapotranspiration (mm day^{-1}); ETo = reference crop evapotranspiration (mm day^{-1}); Kc = crop coefficient. (The Kc values used in this study were 0.76, 1.07, 1.18, and 0.88 for the initial, development, mid-season, and maturity growth stages, respectively, as reported by Ref. [29].)

2.5.3. Amount of Applied Irrigation Water (AIW)

The amount of applied water was measured by a flow meter and was calculated according to the following equation [30]:

$$AIW = \frac{Sp \times S1 \times ETo \times Kc \times Kr \times I\ interval}{Ea} + LR \quad (3)$$

where: AIW = applied irrigation water depth (liters/day); Sp = distance between plants in the same line (m); Sl = distance between lines (m); ETo = potential evapotranspiration (mm/day) values obtained by [7]; Kc = crop coefficient, and Kc ranged between 0.5 to 1.18 during the growing season as recorded by [29] and shown in Table 6; Kr = reduction factor that depends on ground cover. It equals 0.75 for mature trees [31]; Ea = drip irrigation system efficiency = 90%; I interval = irrigation intervals (days) = 1 day for the experimental site; LR = leaching requirements = the extra amount of applied water needed for salt leaching and is calculated according to [26] as follows:

$$\text{LR} = \text{ECiw}/\text{ECe} \tag{4}$$

where ECiw = salinity of irrigation water (dS m^{-1}), and ECe = average soil salinity tolerated by the crop as measured by soil saturated extracts (dS m^{-1}). Under the current experimental conditions, no additional water was added for leaching to avoid any effect on stress treatments.

Data recorded: Leaf parameters such as values of leaf length (cm) and leaflet length and width (cm) were measured; percentage of fruit set: As for fruit set%, the number of flowers as full bloom and set fruitlets were recorded on the tagged limbs; then, the percentage of fruit set was estimated by the following equation according to [32].

$$\text{Fruit set } (\%) = \frac{\text{No. of set fruitlets}}{\text{Total No. of flowers at full bloom}} \times 100 \tag{5}$$

Yield and its components: In October, when fruits reached the (tamer) date stage, the date palms were harvested during the study years. The average fruit yield (kg/palm) and bunch weight (ton/fed) were registered in kilograms. Moreover, samples were randomly collected from four different bunches to determine the values of fruit weight, flesh weight, and fruit pulp weight in gm.

2.5.4. Crop Water Productivity (WP)

WP is a crop yield per unit for applied irrigation water that investigates the effective use of applied irrigation water [33] and is formulated as follow:

$$\text{WP} = \frac{\text{Fruits yield (kg/fed)}}{\text{Applied irrigation water } (\text{m}^3/\text{fed})} \tag{6}$$

Statistical analysis: Data collected during the study period (three seasons) were subjected to variance analysis according to [34]. Using Duncan's multiple range test, the significant differences amongst means were determined [35].

3. Results

3.1. Effect of Soil Amendments, Irrigation Levels, and Their Interactions on

3.1.1. Palm's Water Relationships

The estimated crop evapotranspiration (ETc): Water use by mature palm trees crop (ETc) is determined by multiplying the reference ETo by the palm trees crop coefficient (Kc). The ETc was calculated using the climate data for three seasons to calculate water requirements for the palm trees. Results in Figure 1 illustrate the results of the ETc calculations for the experiment site. The highest monthly ETc was during June and July at (197.7 and 208.6), (197.7 and 215.8), and (198.0 and 213.3) mm/month for the first, second, and third seasons, respectively, while the lowest ETc value was in January and December and was (88.4 and 15.5), (75.3 and 75.3), and (72.5 and 74.7) mm/month in the three seasons, respectively. Generally, the ETc in the 2018 season was higher than ETc in both 2019 and 2020 seasons. These results agreed with those of [29].

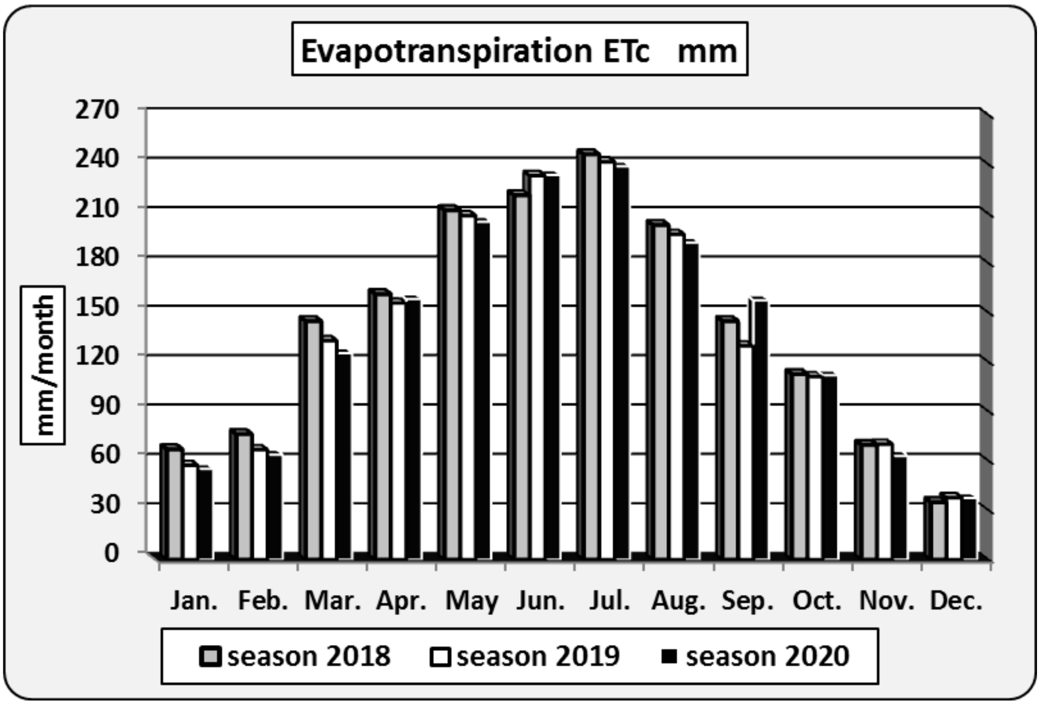


Figure 1. The estimated evapotranspiration (ETc) during the three growing seasons (2018, 2019, and 2020) for experiment site.

3.1.2. Applied Irrigation Water (AIW)

The effect of tested irrigation treatments on applied irrigation water, expressed as liters/tree/day, m^3/fed/month, and m^3/fed/year during the three growing seasons, are shown in Table 7. Results show that the least amounts of water requirements were during January and December regarding the three seasons and the greatest amounts of water requirements during June and July. As for the average amounts of applied irrigation water, they were 5664, 4815, and 3965 m^3/fed/year (mean of the three seasons) for the 100%, 85%, and 70% Etc irrigation treatments, respectively.

The obtained amounts were 1349, 1146, and 944 mm/fed/y for the same respective treatments, and they were consistent with the results concluded by [36]. The results show that the total irrigation water volume for the applied full irrigation treatment is (86, 80) m^3 $palm^{-1}$ $year^{-1}$ [37], as the total annual net water use in the regions ranged between 59.4 and 108 m^3 $palm^{-1}$ $year^{-1}$, according to the geographical location, soil characteristics, and climate elements. The results of this study concluded that the amount of applied irrigation water with soil conditioner for a good yield of palm trees should be $\geq$4815 m^3/fed/y (1146 mm/fed/y). Due to higher evapotranspiration and reduced groundwater recharge, climate change reduces the available quantities of water and increases the need for water in agriculture. Accordingly, the most efficient use of water resources is crucial to improving the provision of water [38].

Table 7. Irrigation treatments effect on the amounts of applied irrigation water for the three growing seasons.

Month	**AIW**	**Irrigation Levels (ETc)**								
		70%	**85%**	**100%**	**70%**	**85%**	**100%**	**70%**	**85%**	**100%**
		1st Season 2018			**2nd Season 2019**			**3rd Season 2020**		
January	L/tree/day	81	98	116	69	84	98	66	81	95
	m^3/fed/month	160	195	229	137	166	195	132	160	188
February	L/tree/day	102	124	145	89	108	127	85	103	122
	m^3/fed/month	182	221	261	160	194	228	152	185	218
March	L/tree/day	175	212	249	160	195	229	151	183	216
	m^3/fed/month	346	420	495	318	386	454	300	364	428
April	L/tree/day	201	244	287	194	236	277	197	239	281
	m^3/fed/month	385	468	550	373	452	532	378	459	540
May	L/tree/day	256	310	365	252	306	360	247	300	353
	m^3/fed/month	507	616	725	499	606	713	491	596	701
June	L/tree/day	276	335	394	276	335	394	276	335	394
	m^3/fed/month	529	642	756	529	642	756	530	643	757
July	L/tree/day	296	360	424	307	372	438	303	368	433
	m^3/fed/month	588	714	840	608	739	869	601	730	859
August	L/tree/day	245	297	350	238	289	340	232	282	331
	m^3/fed/month	486	590	694	472	573	675	460	559	657
September	L/tree/day	180	219	258	162	196	231	190	230	271
	m^3/fed/month	346	421	495	310	377	443	364	442	520
October	L/tree/day	136	165	194	134	163	191	135	164	193
	m^3/fed/month	269	327	385	266	323	380	267	325	382
November	L/tree/day	87	105	124	87	106	125	78	95	112
	m^3/fed/month	166	202	238	167	203	239	151	183	215
December	L/tree/day	42	51	60	45	55	65	45	55	64
	m^3/fed/month	84	102	120	90	109	129	89	108	128
Total	m^3/fed/year	4050	4918	5786	3929	4771	5613	3915	4754	5594

3.2. Effect of Soil Amendments, Irrigation Levels, and Their Interactions on Growth

Leaf Parameters

It is obvious from data shown in Figures 2–4 that the mean values of leaf length (cm) and leaflet length and width (cm) significantly increased with the increasing percentage of soil amendments utilized in this experiment (bentonite, humic substances, and *Bacillus polymyxa*) to reach the maximum results by utilizing the highest percentages of such amendments in the three studied seasons compared to the control ones. This may be attributed to conglomerating the benefits of the three used amendments, as mixing bentonite and humic substances with *B. polymyxa* was more effective in improving the physio-chemical characteristics and fertility of sandy soil. Thus, the growth of cv. Siwi date palm trees thereby improved.

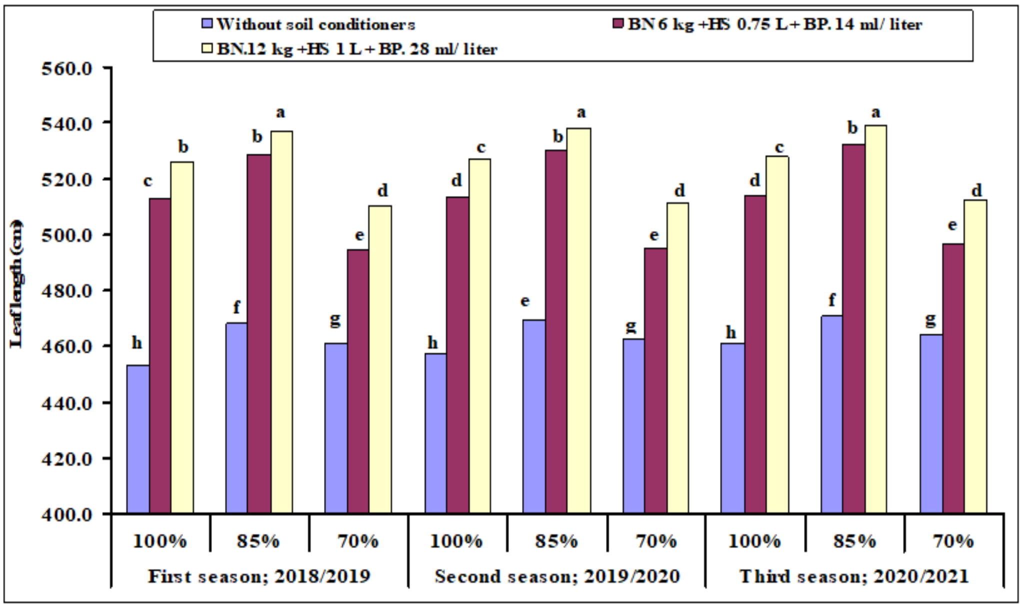


Figure 2. Effects of soil amendments, irrigation levels, and their interactions on leaf length (cm) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

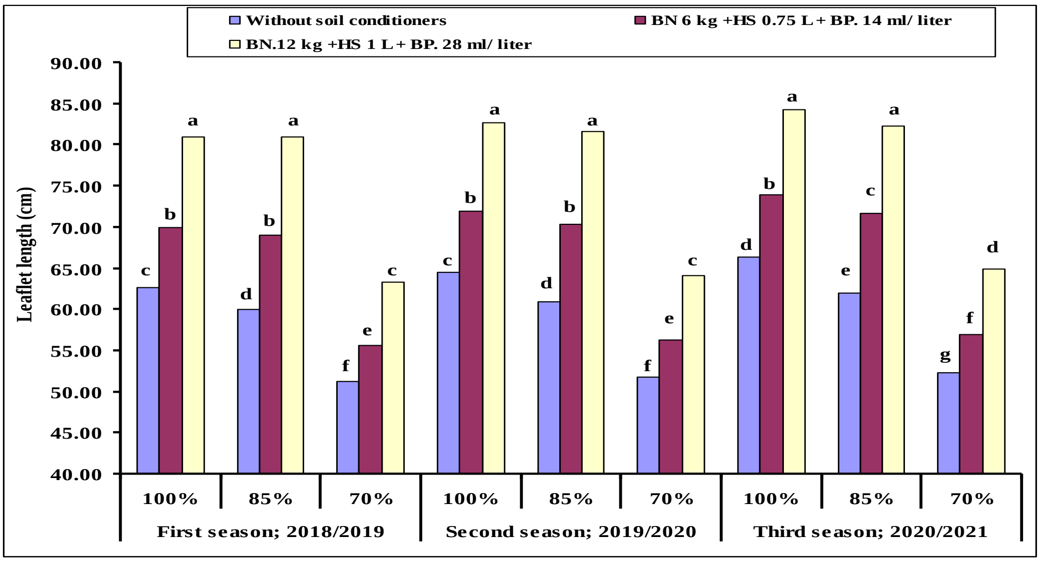


Figure 3. Effects of soil amendments, irrigation levels, and their interactions on leaflet length (cm) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

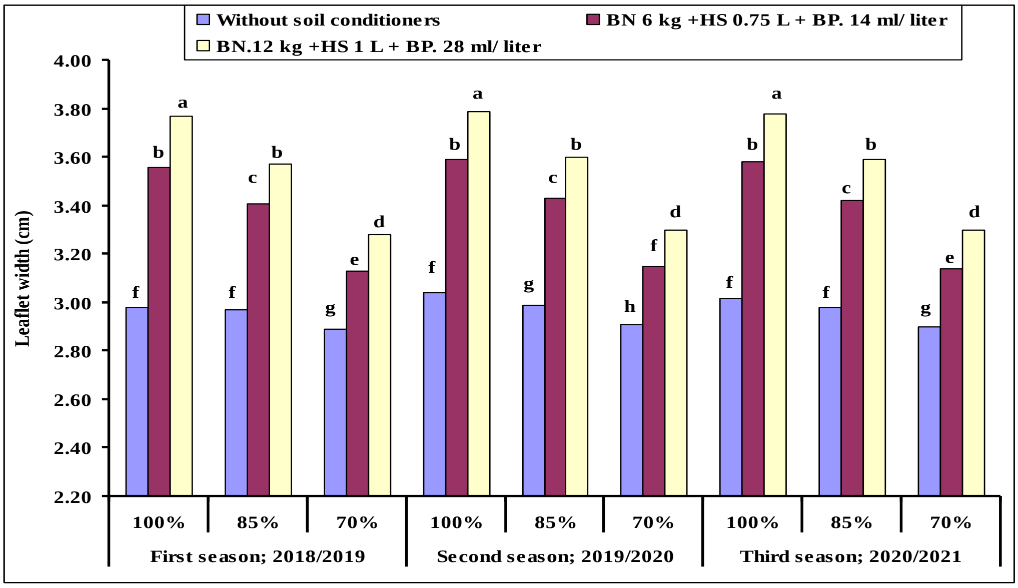


Figure 4. Effects of soil amendments, irrigation levels, and their interactions on leaf width (cm) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

Actually, leaf length was the longest with 85% of ET crop water level in the three experimental seasons, followed by 100% level, whereas the shortest leaf length in the three seasons was attained by 70% of ET crop water level. On the other hand, leaflet length and width means progressively increased with the increase of the irrigation water level to reach its peak by 100% water level. Nevertheless, date palm is considered drought-tolerant and can resist water shortage; it is preferable to provide it with enough water amounts for better growth and higher production.

Likewise, the interaction treatments had a considerable effect on leaf characteristics, where combining between soil supplementation with the highest percentages of the three used conditioners and irrigating with either 85 or 100% of ET crop water level gave the best results in general, with the prevalence of the three soil conditioners (at high rates) along with 100% water level combined with treatments that scored the highest means in most cases of the three growth seasons. However, irrigation of date palm trees amended with the three soil conditioners (at the high rates) with 85% water treatment attained the longest leaf length in the three growth seasons, followed by those grown in the same supplemented soil but irrigated with 100% of ETc water level, with significant differences among themselves in the three studied seasons. This means that increasing irrigation water quantity to the recommended level does not usually improve all growth characteristics.

3.3. Effect of Soil Amendments, Irrigation Levels, and Their Interactions on Yield and Its Components

3.3.1. Fruit Set and Bunch Weight

Results listed in Figures 5 and 6 show that mixing the sandy soil with 12 kg bentonite + 1 L humates + 28 mL/L *B. polymyxa* achieved the highest percentage of fruit set over the other supplementation and control treatments in the three successive seasons. Irrigation with 100% of ET crop water level also registered higher fruit set percentage in the three growth seasons. However, interacting between mixing the sandy soil with the three amendments at high rates and irrigating with either 85 or 100% water level achieved the highest percentage of fruit set in the three growth seasons without significant differences among them.

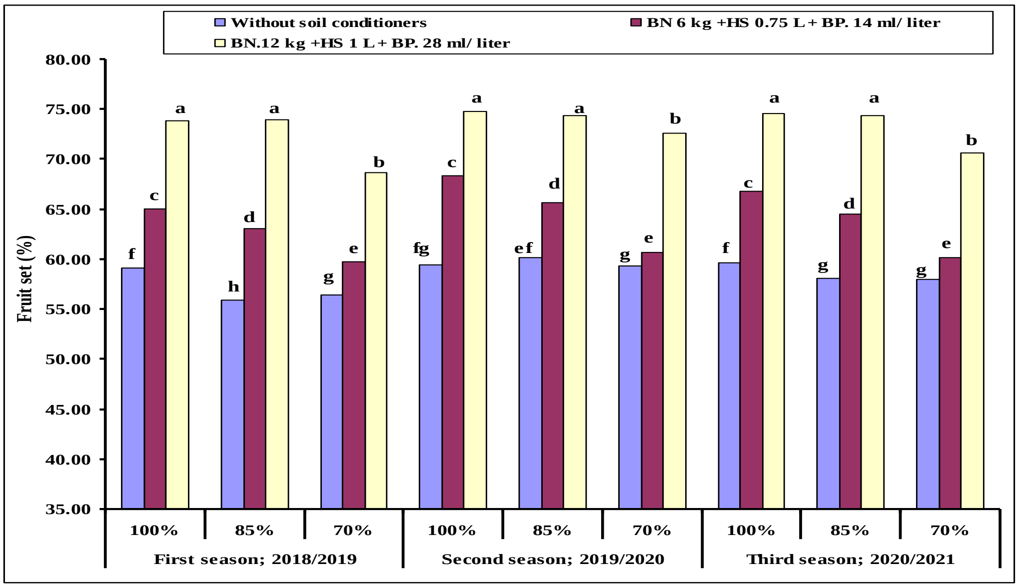


Figure 5. Effects of soil amendments, irrigation levels, and their interactions on fruit set (%) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

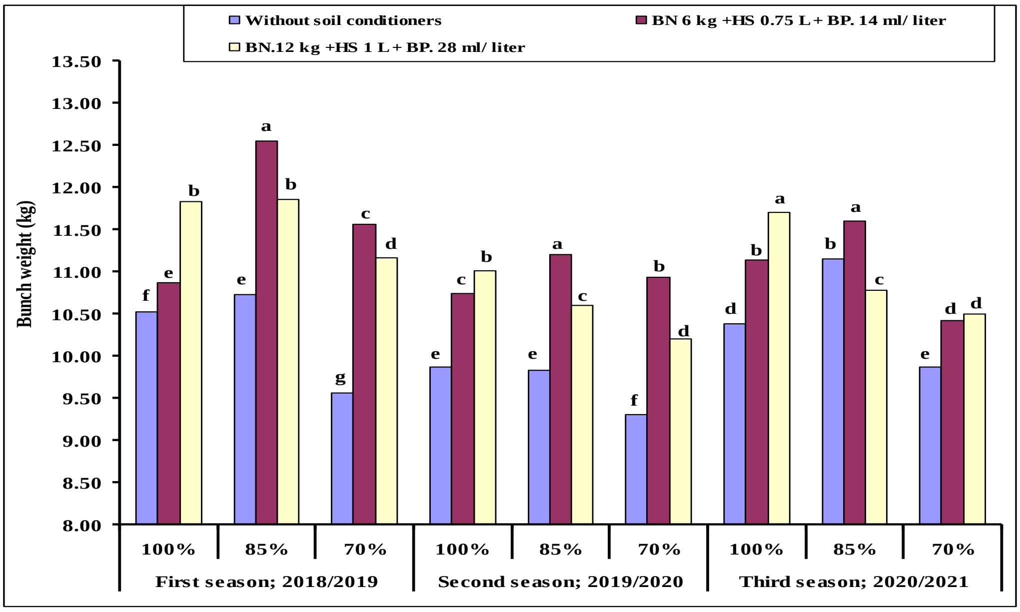


Figure 6. Effects of soil amendments, irrigation levels, and their interactions on bunch weight (kg) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

Bunch weight (kg) was found to be maximum by mixing the sandy soil with the three used soil conditioners at either low or high rates in the first and third seasons, while bunch weight (kg) was found to be maximum by mixing the sandy soil with the three used soil conditioners in the second season by applying the three conditioners at only the low rate. In addition, irrigation with 85% of ET crop water level registered the heaviest bunch weight in the first and third seasons. As for the second season, irrigation with both 85 and 100% water levels gave bunch weights on par with each other. Accordingly, combining between amending the sand with the low rate of bentonite (6 kg), humic substances (0.75 L), and *B.*

polymyxa (14 mL/L) and the medium water level (85% of ETc) elevated the bunch weight to the highest values over all the other interactions in the three studied seasons.

3.3.2. Yield Components

In an identical response to that of leaf characteristics, fruit set and bunch weight were also obtained regarding yield components attributes shown in Figures 7 and 8, as yield of palm tree (kg/palm) and feddan (ton/fed) successively increased with increasing soil conditioners rates to reach the maximal values by amending the soil with 12 kg bentonite + 1 L humates + 28 mL/L *B. polymyxa* treatment, which achieved the highest yield either per palm tree or per feddan, with few exceptions in the three growth seasons.

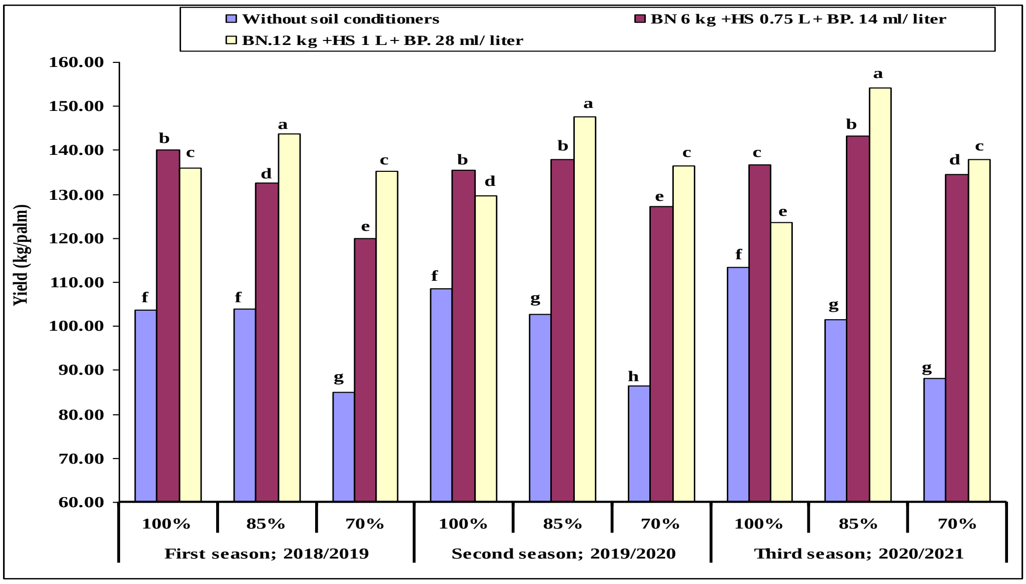


Figure 7. Effects of soil amendments, irrigation levels, and their interactions on yield (kg/palm) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according t Duncan's Multiple range test.

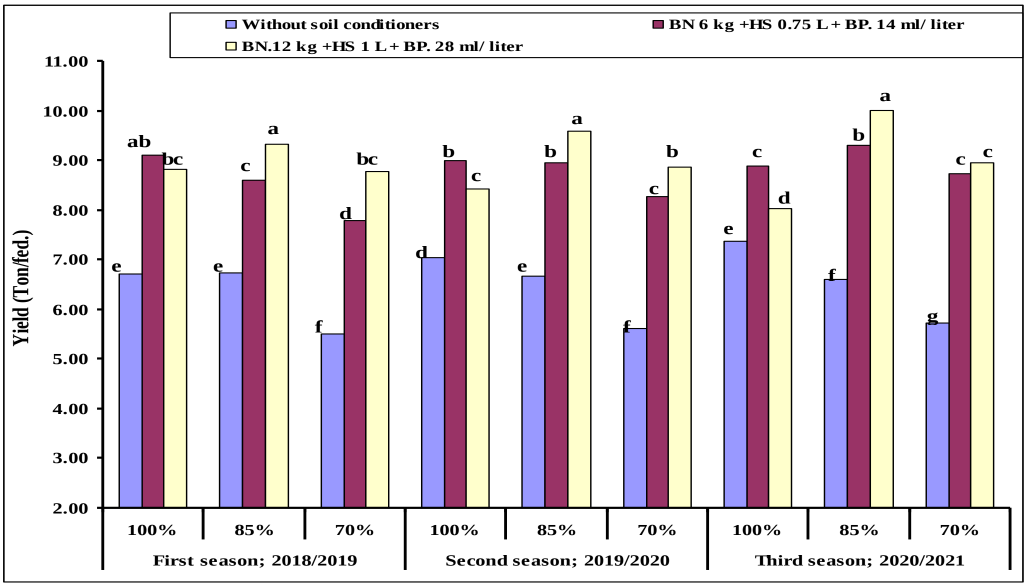


Figure 8. Effects of soil amendments, irrigation levels, and their interactions on yield (ton/fed) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

On the other hand, palm yield (kg) improved by raising irrigation water amount to either 85 or 100% of ET crop, with the superiority of 85% water level, which attained the highest yield in the three seasons. That was true for the yield of feddan (ton) in the first, second, and third seasons, where 85% water level registered 8.23, 8.41, and 8.69 ton/feddan compared to 7.37, 7.59, and 7.81 ton/fed for control treatment in the three growing seasons, respectively. This indicates that increasing the water amount to level 100% of ET crop does not result in additional growth increments in either palm or feddan yield.

As for the effect of interactions, results in Figures 7 and 8 show that all interaction treatments significantly hastened both yield/palm and yield/fed compared to the control one in the three seasons, but the prevalence was for the combination of adding three soil conditioners (at the high rate) + 85% water level, which achieved the highest yield/palm and yield/fed compared to all the other combinations in the first, second, and third seasons.

3.4. Fruit Characteristics

The results of fruit characteristics presented in Figures 9–11 are similar, and they indicate that the mean values of fruit weight (g), fruit pulp weight (%) and flesh weight (g), significantly increased in response to amending the sandy soil with bentonite, humic substances, and *B. polymyxa* soil conditioners at either a low or high rate compared to the control means in the three studied seasons. Although these two amending treatments switched their benefit effects in improving fruit characteristics characters in the three seasons, the dominant impact was that of applying the three soil conditioners at the low treatment rates (6 kg bentonite + 0.75 L HS + 14 mL *B. Polymyxa*), which achieved better results in most fruit measurements than the high rate.

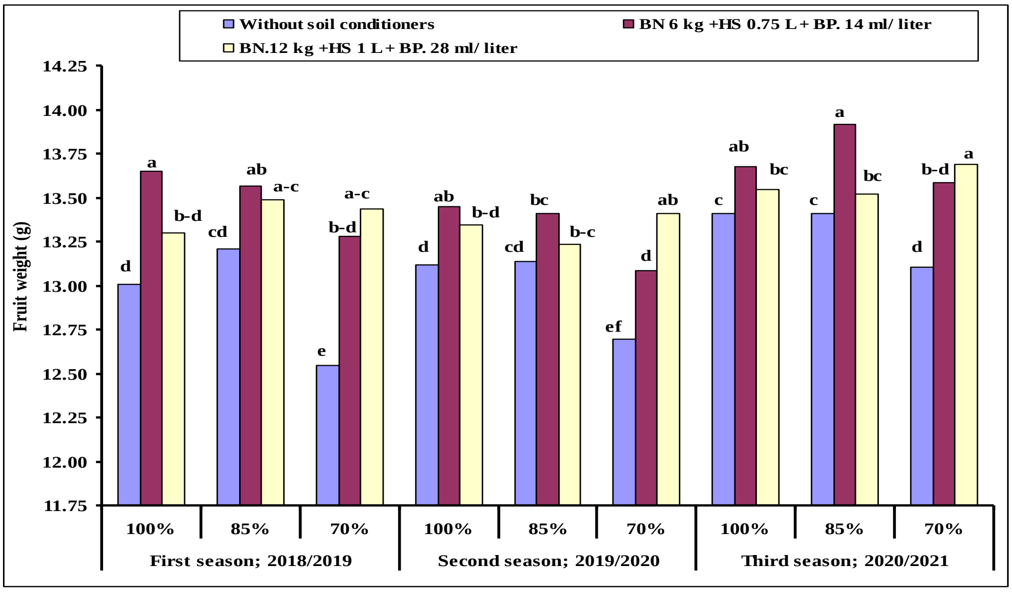


Figure 9. Effects of soil amendments, irrigation levels, and their interactions on fruit weight (g) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

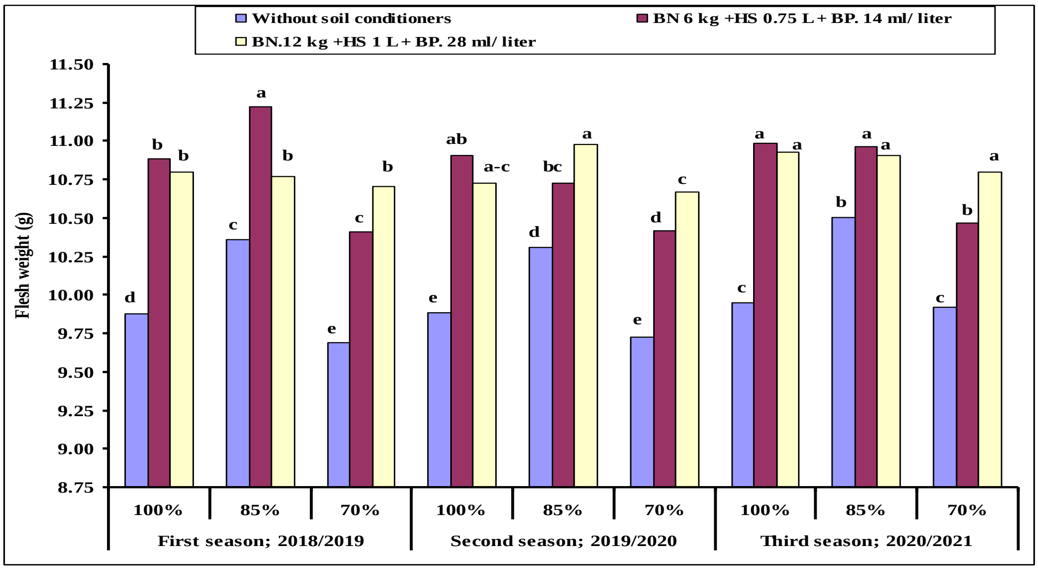


Figure 10. Effects of soil amendments, irrigation levels, and their interactions on flesh weight (g) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

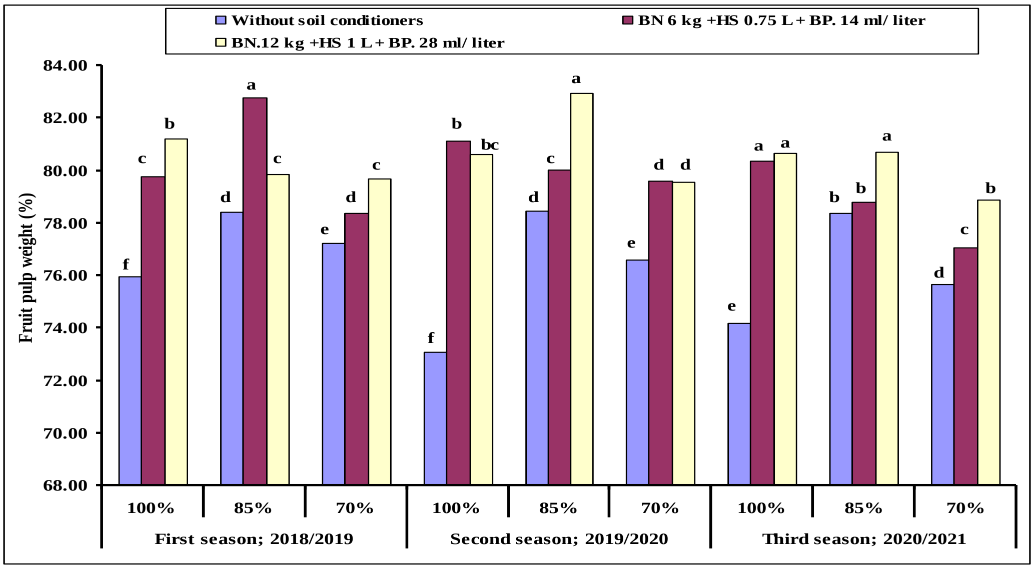


Figure 11. Effects of soil amendments, irrigation levels, and their interactions on fruit pulp weight (%) of *Phoenix dactylifera* L. var. Siwi tree during the three studied seasons. Note: The same letter are not significantly different at 5% level according to Duncan's Multiple range test.

The same results were also achieved regarding the effect of irrigation water treatments, where, increasing water quantity used for irrigation from 70% to either 85 or 100% of ET crop, the mean values of all fruit criteria significantly increased with various difference levels relative to the means of control level in the three experimental seasons. In addition, the medium (85%) and high (100% of ET crop) water treatments also achieved good results, but the upper hand in the three seasons was for irrigation with 85% treatment level, which achieved higher means than the 100% treatment level in most measured fruit parameters.

Regarding the effect of interaction treatments, results in Figures 9–11 show that the means of fruit characteristics fluctuated due to the combination of the soil conditioners treatments used in this study with irrigation of both 85 and 100% of ET crop water level, achieving significant increments in different fruit parameters obtained in the three seasons in general. However, combining the amendment of the three soil conditioners at low rates (bentonite at 6 kg + HS at 0.75 L + *B. polymyxa* 14 mL/L) with the medium level of irrigation water (85% of ETcrop) achieved the best results and gave the maximum values in most fruit characteristics.

3.5. Effect of Soil Amendments, Irrigation Levels, and Their Interactions on Water Productivity

Crop Water Productivity (WP)

Water productivity (WP) is used to describe the relationship between production and the amount of applied irrigation water. It is clear from Figure 12 that this characteristic was markedly profitable under the lowest amount of irrigation water (ETc 70%), as it registered 1.82, 1.92, and 1.98 Kg fruits/m^3 of irrigation water in the first, second, and third seasons, respectively. On the other hand, when increasing the amounts of the applied irrigation water (ETc 100%), they produced the smallest values (1.42, 1.45, and 1.43 kg fruits/m^3) of irrigation water in the first, second, and third seasons, respectively.

Water conservation benefits can be obtained by allowing plants to experience moderate water stress. Supplying water to the crop at levels below evapotranspiration (ET) levels considerably allows crops to sustain some degree of water deficit without significant yield reduction but with significant water savings.

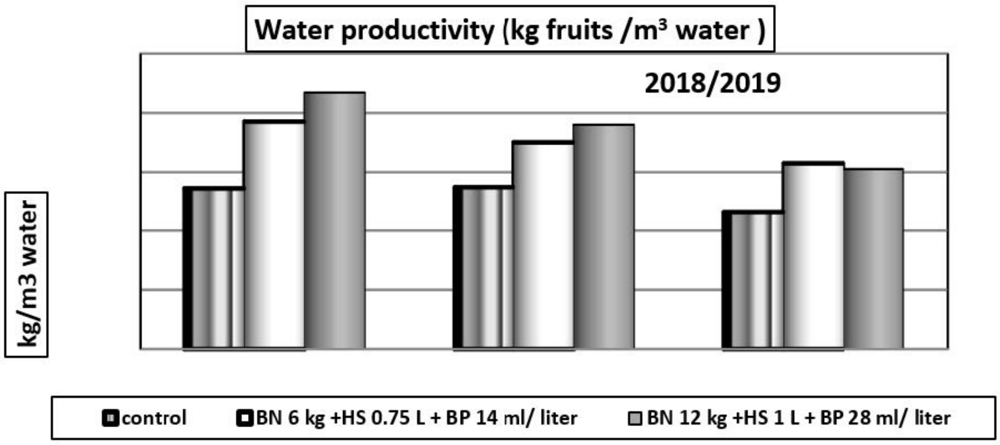
On the other hand, the control under all irrigation treatments gave quite lower water productivity, greatly lower than that given by the applied conditioners. The lowest water productivity (WP), 1.30, 1.36, and 1.38 kg fruits/m^3 of irrigation water by the control treatment, was obtained.

However, water utilization efficiency progressively increased with applied soil conditioners in comparison to the control one, which increased the WP by averages of 36.7 and 41.5% for BN 6 kg +HS 0.75 L + BP. 14 mL/L and BN 12 kg +H 1 L + BP. 28 mL/L, respectively.

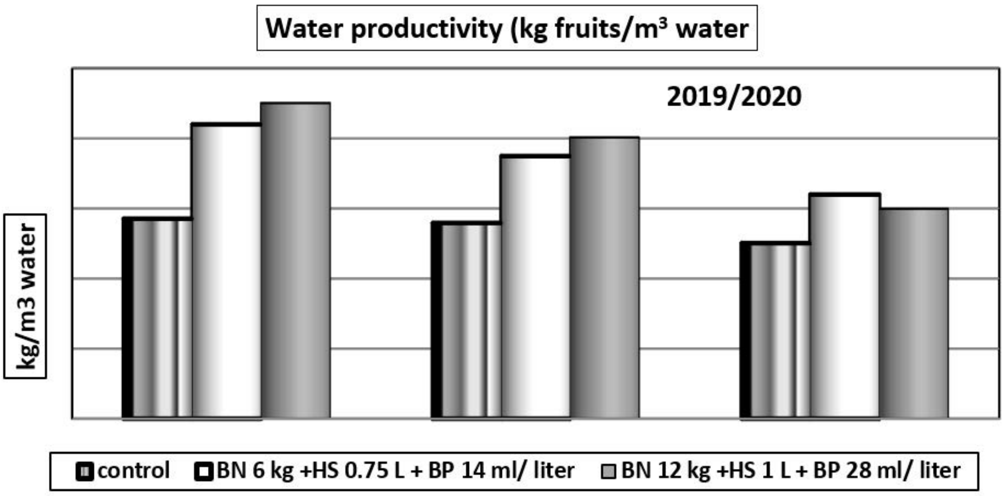
Additionally, water productivity (WP) increased under the treatment of 70% of Etc combined with soil conditioners BN (12 kg) + HS (1 L) + BP. (28 mL/L), and values were 2.17, 2.25, and 2.27 kg fruits/m^3 as compared with the full irrigation (100% Etc) treatment values standing at 1.16, 1.25, and 1.31 kg fruits/m^3, respectively.

3.6. Economic Analysis

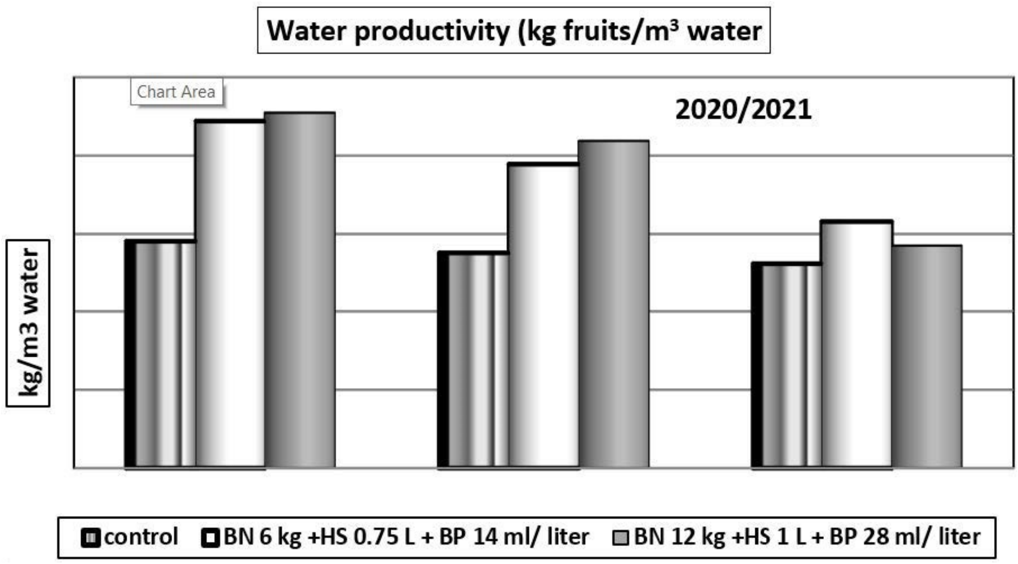
Total cost, gross return, and net return of palm trees as affected by different amounts of irrigation water and organic and inorganic soil conditioners treatments are shown in (Table 8). The highest net return of 84144 EGP./fed and 79166 EGP./fed were obtained from 85%ETcrop with BN (12 kg) + HS (1 L) + BP (28 mL/L) and BN (6 kg) + HS (0.75 L) + BP (14 mL/L) (in average of the three seasons), respectively. These treatments represent the best choice for high net return under the study conditions compared with the control ones.



(**a**)



(**b**)



(**c**)

Figure 12. Effect of irrigation water amount and soil conditioners rate on water productivity (WP) (kg fruits/m^3 water) of palm trees during (**a**) 2018, (**b**) 2019, and (**c**) 2020 seasons.

Table 8. Economic analysis as affected by amount of irrigation water and organic and inorganic soil conditioners treatments (average yield and applied water of the three years).

Treatments		Cost of Production (EGP./fed)					Income Profits (EGP./fed)			Net Return (EGP/fed)
		Field Practices	Cost of Add	Soil Conditioner	Water	Total (EGP/fed)	Fruit (EGP/Kg)	Kg/fed	Total (EGP/fed)	
70% of ETc	Without soil conditioners	7000	0.0	0.0	991	7991	10	5623	56,230	48,239
	BN (6 kg) + HS (0.75 L) + BP. (14 mL/L)		320	1990	926	10,236	10	8273	82,730	72,494
	BN (12 kg) + HS (1 L) + BP. (28 mL/L)		320	3980	894	12,194	10	8873	88,730	76,536
85% of ETc	Without soil conditioners	7000	0.0	0.0	1204	8204	10	6677	66,770	58,566
	BN (6 kg) + HS (0.75 L) + BP. (14 mL/L)		320	1990	1124	10,434	10	8960	89,600	79,166
	BN (12 kg) + HS (1 L) + BP. (28 mL/L)		320	3980	1086	12,386	10	9653	96,530	84,144
100% of ETc	Without soil conditioners	7000	0.0	0.0	1416	8416	10	6503	65,030	56,614
	BN (6 kg) + HS (0.75 L) + BP. (14 mL/L)		320	1990	1323	10,633	10	8953	89,530	78,897
	BN (12 kg) + HS (1 L) + BP. (28 mL/L)		320	3980	1277	12,577	10	8740	87,400	74,823

Note: L.E., Egyptian pounds. USD 1 = EGP. 18

4. Discussion

Bentonite as a natural soil conditioner improves the coarse texture of soils; absorbs large amounts of water, giving a volume equaling approximately 15 times of its dry bulk; and also has a high cation exchange capacity [13]. Application of bentonite to sandy soil improves water movement downwards, prevents water loss, keeps the minerals from leaching out [39], and enhances the physiochemical properties and soil moisture cation exchange capacity in particular [5]. Humic substances influence the plant growth through either the amelioration of physical, chemical, and biological conditions of the soil or by promoting metabolic activity in plant growth [40]. In addition, humus improves soil fertility through raising the soil microbial population, including beneficial microorganisms, such as *Bacillus polymyxa*, which decomposes organic matter, renders nutrients, and makes them more available for plants [41]. This may be reasonable because sufficient water supplies the plants with their water requirements necessary for healthy growth [42]. Thus, the saving and maximization of WUE for date palm trees grown either in sandy soil or in arid and semi-arid regions through applying organic and biofertilizers has become the key for sustainable production [8]. The results of this current study are consistent with those results concluded by [13], who indicated that the amelioration of canopy diameter in Deglet Nour date palm trees reached 226 $\pm$ 0.6 cm in sandy soil mixed with farm manure and bentonite clay treatment compared to 172 $\pm$ 0.6 cm in untreated palm trees. The height of the palm trees increased by 69 $\pm$ 0.8 cm from 29 $\pm$ 0.1 cm under the control treatment, and the number of leaves increased from 40 leaves/palm tree in sandy soil mixed with only bentonite to 60 leaves/palm tree in sandy soil mixed with both farm manure and bentonite. Furthermore, [43] recommended to apply 2 kg of Nile fertile + 500 g K_2SO_4 with irrigation level of 11 m^3/tree/year to enhance the means of the number of the new shoots, the shoot length and diameter, the number of leaves/shoots, and leaf area parameters to the highest values in the Arabi pomegranate tree. Ref. [12] found that the highest irrigation level of 11 m^3/tree/year and application of either Hundz soil at a rate of 10 kg/tree or the mixture of Nile fertile+ K_2SO_4 at 2 kg + 500 g rate improved fruit set of 10-year-old Arabi pomegranate trees grown in sandy soil under drip irrigation. Similar observations were also obtained by [3,11,44,45] on various varieties of date palm. These results are in great accordance with those discovered by [12], who postulated that farm manure (M) and bentonite clay (B) noticeably improved the yield of the 3-year-old Deglet Nour date palms growing in sandy soil. The sand (S) mixed with either manure (M) or with both bentonite (B) and manure (M) obtained yields of 70 $\pm$ 0.9 kg/palm and 80 $\pm$ 0.5 kg/palm, respectively. This might partially alleviate the alternate-year bearing of this date palm variety. Likewise, [43] revealed that applying 2 kg/tree Hundz soil + 2 kg Nile fertile + 500 g K_2SO_4 with irrigation level of 11 m^3/tree/year produced the highest yield and good quality of Arabi pomegranate fruits, and applying the same three previous amendments at the same rates under an irrigation level of either 8.25 m^3/tree/year or 5.5 m^3/tree/year for saving 25–50% of water achieved the same yield as well. [12] On 3-year-old Deglat Nour date palms grown in sandy soil, the authors pointed out that sand amended either with farm manure or with bentonite clay and farm manure improved fruit quality compared to the untreated sand. Likewise, [43] pointed out that fruit quality (fruit weight, diameter, and length) of Arabi pomegranate trees greatly improved by supplementing the sand with either Hundz soil (5 or 10 kg/tree) or mixture of Nile fertile + K_2SO_4 (1 kg + 250 g or 2 kg + 500 g) under irrigation levels of 50, 75, and 100% of ET crop water levels, which were 5.5, 8.25, and 11 m^3/tree/year. Accordingly, the results are in agreement with [46], who indicated water productivity gains by decreasing the amount of used water; ref. [21] also indicated that applying deficit irrigation to palms in dry areas can maximize water productivity (WP); however, water productivity (WP) significantly increased with decreasing the irrigation water amount [47]. Earlier studies indicated that deficit irrigation strategies can improve WP and save irrigation water in several important horticultural crops, especially those that are typically tolerant of water stress [48]. Water productivity (WP) for date palms of many date-producing countries ranges as a general average of 0.18–0.37 $kg{\cdot}m^{-3}$ [4]. Bentonite increased soil moisture and soil water storage as well as millet yield and water efficiency, and ref. [49,50] asserted that soil conditioners, whether natural or organic, contributed significantly to providing a reservoir of soil water to plants when needed in the upper layers of the soil, which is the zone where root systems normally grow. Likewise, shale sediments (bentonite) applied at different rates to sandy soil improved its physicochemical properties, including soil moisture [5].

5. Conclusions

Based on the previous results, it is recommended to apply bentonite, humic substances, and *B. polymyxa* at either low (BN (6 kg) + HS (0.75 L) + BP (14 mL/L)) or high (BN (12 kg) + HS (1 L) + BP (28 mL/L)) rates to the sandy soil and irrigate with 85% and 70% of ETc water level to obtain the best growth, highest yield, optimal quality, and water-use efficiency along with gross economic return from planting Siwi date palm trees in sandy soil under oasis agro-system conditions.

Author Contributions: Conceptualization, M.M.S.-B., K.H.A.H. and M.F.E.-K.; methodology, software, formal analysis, data processing, and writing—original draft preparation, K.H.A.H., M.F.E.-K. and S.D. writing—review and editing, S.A., K.H.A.H. and M.F.E.-K.; funding acquisition, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by King Saud University (grant number RSP-2021/241).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Relevant data applicable to this research are within the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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