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Sustainable Biochar Outperforms Hydrogel in Alleviating Water Stress, Enhancing Zebda mango Yield and Water Use Efficiency

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WATER scarcity in arid regions is common, but deficit irrigation is a challenge to address climate change and growing water needs. Effective water conservation management is crucial for addressing climate change sustainability and mitigating water scarcity. So, the aim of this study to evaluate the effectiveness of biochar at 7 and 14 kg/tree, hydrogel at 50 and 100 g/tree as water-saving agents in mitigating the negative effects of deficit irrigation at 70% and 85% of irrigation requirements (IR) in Zebda mango variety. The results indicated that reducing the irrigation level from 85% IR to 70% IR led to a significant reduction in plant growth, fruit retention, yield, and quality, as well as water use efficiency (WUE). However, biochar and hydrogel, particularly at high levels, successfully alleviated water stress in mango Zebda trees. Moreover, biochar significantly outperformed the impact of hydrogel in alleviating water stress by enhancing plant growth, fruit set and fruit quality. Treatment of 14kg biochar increased fruit yield by 35.1% and 54.5 % as well as improvement in WUE by 34.7% and 54.9% for 85%IR and 70% IR as mean of both seasons. Furthermore, biochar at 14kg surpasses hydrogel at100g by 21.16% and 20.99% in terms of yield and WUE under 70% IR. Biochar and hydrogel successfully mitigated deficit irrigation effects, suggesting future research use 100% or 85% deficit irrigation during flowering, fruit set, and growth, and 70% at other stages.

Keywords: *Mangifera indica;* chlorophyll; fruit; irrigation; proline.

1. Introduction

Water stress, an abiotic stress, can have a significant impact on the growth, morphological traits, and biochemical and physiological aspects of plants. If pressure occurs during the critical stages of plant growth, it could lead to a decrease in crop production. The increasing population in Egypt is causing a significant gap in irrigation water supplies, posing a threat to food security and water poverty (less than 1000 m3 of water per person per year), and requiring effective irrigation scheduling strategies for timely and accurate crop delivery (Abdelhaleem et al., 2021). Agriculture consumes 70% of Earth's freshwater, making optimization of water resource use crucial for long-term competitiveness. Water scarcity is a major issue, especially in arid and semi-arid regions. Climate change's effects on agriculture could worsen the competition for resources like soil, water, and energy, hindering efforts to supply enough food for the expanding world population (Wheeler and von Braun, 2013).

Mango (*Mangifera indica* L.) is among the oldest and most favored tropical fruits globally. In Egypt, mango is considered as one of the most popular fruit crops. The area of mango orchards reached 281,153 feddan, producing 880,875 tons of fruit annually average productivity 4.150 tons/feddan (Ministry of Agriculture, 2016). Mango is grown in over 100 countries, being commercially cultivated from the equator to the subtropical regions in the north and south. This minimum applies to a tropical region with temperatures rarely falling below 18°C. Additionally, it includes the subtropical zone, where winter minimum temperatures typically range from 5-10°C (Galán and Lu 2018). Mango farming, a significant global agricultural practice, produces over 40 million tons annually. India is the top producer, with Mexico controlling 20% of global trade while, Brazil and Peru (18%) are the main exporters to the European Union, with Spain contributing 7% (Evans et al., 2015; OPM 2020). Deficit irrigation technique has been purposed in several crops, such as pomegranate (Fayek et al., 2022a), grapevine (Fayek et al., 2022b) and mango (Spreer et al. 2009; Dos Santos et al., 2014; Shaban et al., 2020; Shaban et al., 2021) as strategy for saving water under drought conditions. These studies show water and energy saving, fruit quality improvement and yield increase as well as water use efficiency (WUE), particularly under conditions of light or moderate deficit irrigation (Dos Santos 2014; Abu-Hashim and Shaban, 2017; Abdel-Aziz 2017; Yassin et al.,2021; Abdel-Sattar et al., 2024).

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Another approach to deal with water stress is the use of water-saving agents, which are seen as a way to address the issue of water scarcity. Hydrogel is a high-molecular-weight, multi-linkage polymer used to combat water scarcity, absorbing 400-1500 g of water per dry gram. Its high molecular weight allows for efficient liquid absorption (Hüttermann et al., 2009; Akhter et al., 2004). Hydrogel polymers improve plant growth by increasing soil water holding capacity and delaying wilting, enhancing drought tolerance and overall growth (Ekebafe et al., 2011). They improve water use efficiency, decrease irrigation frequency, and promote plant growth. Hydrogel increases yield, water retention, and microbial activity in various plants (Pattanaaik et al., 2015). More recently hydrogel succeeded in increasing vegetative growth, yield and water use efficiency of olive (Chehab et al., 2017) and mandarin trees (Kato and Tabi, 2023).

Biochar is a carbon-rich byproduct from pyrolyzing organic materials during biofuel production (Lehmann, 2007). It contains highly condensed aromatic structures that resist decomposition in soil, effectively trapping carbon for years (Lehmann et al., 2006 and Novak et al., 2009). Biochar benefits include improved plant growth, enhanced soil water retention, reduced crop disease, decreased heavy metal and toxin availability, altered soil microbial populations, and decreased nutrient leaching (Ghazouani et al., 2023; Murtaza et al., 2024; Akram, et al., 2024). Studies have shown that applying biochar at rates 2, 4, and 6 ton/feddan to apple trees leads to higher yields, improved quality traits, and water productivity under deficit irrigation conditions (Abdelraouf et al., 2017; Singh et al., 2025). Similarly, applying biochar for four harvest-years results in higher grape productivity without significant differences in quality parameters (Genesio et al., 2015) as well as in field crop (El-Sherpiny et al., 2023).

Water scarcity for irrigation is common in dry and semi-dry environments. Additionally, water deficit irrigation management is becoming essential due to the growing need for water in agriculture, industry, and human livelihood. Therefore, the aim of this study is to mitigate the negative impact of moderate (85%IR) and severe deficit irrigation (70%IR) technique on the mango cultivar Zebda using hydrogel and biochar as water-saving agents.

2. Materials and Methods

2.1. Soil properties and irrigation water analyses

Representative soil samples have been taken from the depths 0-15, 15-30 and 30-45 cm. Irrigation water that goes throughout the experimental area was gained from an irrigation channel (Nile River water). Soil physical and chemical properties and also chemical properties of the irrigation water were determined as follows:

2.1.1. Physical properties of soil

Soil particle volume distribution was conducted according to Pipette method. Soil moisture content at field capacity (FC) and permanent wilting point (PWP) were determined (Gee and Bauder (1986).

Table 1. Physical properties of soil.

	Particle Size distribution %				**Texture Class**	**FC**	**PWP**	**AW**	**BD (g/cm^3)**	**TP (%)**
Depth (cm)	**C.Sand**	**F. Sand**	**Silt**	**Clay**						
0-15	14.87	78.90	4.40	1.83	Sand	10.50	4.16	6.34	1.58	40.38
15-30	14.91	78.93	4.30	1.86	Sand	10.40	4.10	6.30	1.60	39.62
30-45	14.89	78.73	4.41	1.97	Sand	10.46	4.13	6.33	1.64	38.11
45-60	14.96	78.66	4.39	1.99	Sand	10.45	4.20	6.25	1.66	37.36

FC: Field capacity; PWP: Permanent wilting point; AW: Available water; B.D: Bulk density, and TP: Total Porosity.

2.1.2. Chemical properties of soil

Soil chemical properties were measured in the laboratory of Soil Dept. NRC as follows: Soil pH and EC were measured in 1:2.5 (soil: water suspension) and in soil paste extract, respectively. Results of these analyses are shown in Table (2).

Table 2. Soil chemical properties.

Depth (cm)	EC, dS/m	pH 1:2.5	Soluble Cations, mq/L				Soluble Anions, mq/L			
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{--}	Cl^{-}
0-15	0.35	8.30	0.50	0.42	1.05	0.23	0.00	0.11	0.82	1.27
15-30	0.36	8.20	0.51	0.43	1.04	0.24	0.00	0.13	0.86	1.23
30-45	0.34	8.30	0.55	0.41	1.05	0.23	0.00	0.12	0.85	1.27
45-60	0.73	8.40	0.57	0.43	1.06	0.25	0.00	0.17	0.86	1.28

2.1.3. Chemical properties of irrigation water

Chemical analysis of irrigation water was measured with using the standard methods and shown in Table (3). All the measured chemical parameters describe the status of the irrigation water and it can be used normally in irrigation.

Table 3. Chemical properties of irrigation water.

pH	EC, dS m^{-1}	Soluble cations, mq/L				Soluble anions, mq/L				SAR
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{-}	Cl^{--}	
7.20	**0.36**	**0.75**	**0.23**	**2.50**	**0.11**	**0.00**	**0.90**	**0.33**	**2.52**	**3.67**

2.2. Experimental details and treatments

This investigation was conducted during two growing seasons (2020-2021 and 20221-2022) on 15-year-old Zebda mango trees. The trees were planted at 5 X 3 m , and they were cultivated in sandy soil at the farm of Agricultural Production and Research Station (APRS), National Research Centre (NRC), El Nubaria Province, El-Behaira Governorate, Egypt (latitude 30.8667 N, and longitude 30.1667 E). The trees were treated with the common horticultural practices. The physical and chemical analysis of soil and chemical analysis of irrigation water was tabulated in Table 1, 2 and 3.

2.2.1. Mango irrigation requirements

According to Allen et al. (1998), the crop coefficient (Kc) and Penman-Monteith equation were used to compute the daily irrigation water requirements. The volume of irrigation water applied for the first season from 1/9/2020 to 30/8/2021 and the second season from 1/9/2021 to 30/8/2022 were calculated using Equation 1 and amounted to 3696 & 3652 m3 /fed./season and 3044 & 3008 m3 /fed./season respectively for 85% and 70% IR (Ttable 4).

Irrigation requirements (IR) were calculated according to Allen et al. (1998) as following equation:

IRg = [ETO x Kc] / Ei - R + LR

Where Kc = crop factor (Allen et al., 1998), Ei = irrigation efficiency (assumed 90%), R, mm rainfall and ETO = reference evapotranspiration, mm/day (estimated from the Central Laboratory for Climate - Agricultural Research Centre Egyptian Ministry of Agriculture at El-Nubaryia farm and according to Penman-Montei; The amount of water needed for salt leaching was determined as the ratio of irrigation water salinity to drainage water salinity, or LR, mm. There was a three-day interval between irrigations. The irrigation schedule involved collecting daily water requirements for three days, adding it to mango trees, and estimating dripper discharge based on 85% and 70% treatments, applying water needs at the beginning of each season.

Table 4. Details of estimating and calculating the volumes of irrigation water added during the two growing seasons.

Item	2020/2021				2021/2022			
	Init. stage	**Dev. stage**	**Mid. stage**	**late stage**	**Init. stage**	**Dev. stage**	**Mid. stage**	**late stage**
ET_O, mm/day	4.90	2.63	5.50	5.23	4.88	2.61	5.47	5.20
Kc (Durán et al., 2019)	0.43	0.55	0.67	0.65	0.43	0.55	0.67	0.65
Ei,%	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
R, mm/ day	0.10	0.67	0.20	0	0.12	0.69	0.22	0
LR,(5%), mm/ day	0.11	0.07	0.22	0.21	0.11	0.04	0.18	0.18
IRg, mm/ day	2.23	0.90	3.86	3.76	2.20	0.86	3.82	3.74
Days of each age stage (FAO 56)	60	90	120	95	60	90	120	95
IRg, mm/stage	133.8	81	463.2	357.2	132	77.4	458.4	355.3
IRg, mm/season	1035.2				1023.1			
IRg, m^3/ fed.$^{-1}$/season (85% IR)	**3696**				**3652**			
IRg, m^3/ fed.$^{-1}$/season (70% IR)	**3044**				**3008**			

ETo: reference evapotranspiration, Kc: crop coefficient, Ei: irrigation efficiency, R: Rainfall, LR: the ratio of irrigation water salinity to drainage water salinity, IRg: Gross Irrigation Requirement; fed=4200m2.

2.2.2. Treatments

Half of the trees were irrigated with 85% of their irrigation requirement (85%IR) levels, while the other half received 70%IR. Every group of irrigation treatments was split into five subgroups that were each treated with either 7kg biochar, 14kg biochar, 50g hydrogel (STOCKOSORB® 500), 100g hydrogel, or non-treated as a control. Each treatment consisted of three replicates, each one contain 9 trees. The different treatments include T1 (85%IR), T2 (85%IR + 7kg biochar), T3 (85%IR + 14kg biochar), T4 (85%IR + 50g hydrogel), T5 (85%IR + 100g hydrogel), T6 (70%IR), T7 (70%IR + 7kg biochar), T8 (70%IR + 14kg biochar), T9 (70%IR + 50g hydrogel), and T10 (70%IR + 100g hydrogel).

2.2.3. Biochar Description

Biochar is a kind of functional material with high carbon content, rich pore structure, and strong adsorption capacity, which is made by pyrolysis and carbonization of biomass under hypoxia conditions. Biochar was prepared using casuarina (Casuarina equisetifolia) wood branches collected locally (without drying) and after produced biochar under 500 °C in an oxygen-limited environment (Zhao and Wang, 2017) the sample was taken to analysis as below (Table 5).

Table 5. Chemical properties of biochar.

Parameter	Value	Parameter	mg/Kg	Parameter	mg/Kg
Moisture %	3.18	P	23000	Cu	98
C %	66.4	K	13700	Mn	87
Ash %	18.58	Ca	24800	Zn	107
PH	8.94	Mg	28300	Na	10800
EC (ds/m)	1.25	S	481		
N %	1.58	Fe	328		

2.2.4. Hydrogel description

A white, granular, water-absorbent polymer (Table 6).designed to enhance the water holding capacity of soil and growing media by acting as a water reservoir which is available to all growing plants. It can hold up to 700 times its own weight in water (STOCKOSORB® 660, Advance Landscape Systems, New Zealand).

Table 6. Properties of hydrogel (STOCKOSORPO 660).

Parameter	Value	Parameter	Value
Potassium polyacrylate, cross-linked	>=95%	pH (1.0 g/l water)	7.7
Physical state	Solid	Vapor pressure (20 'C)	< 20 hPa
Form	Powder	Density	0.7 g/cm3
Color	White	Bulk density	600 kg/m3
Odor	Odorless	CAS-Number	25608-12-2

2.2.5. Experimental design, irrigation and soil amendment treatments

Irrigation and soil amendment treatments were started at November (the time of flower bud induction and differentiation in mango grown in Egypt) till harvesting at August in the second season 2021-2022. In first season, each tree was irrigated with 13.20m3 and 10.87m3/year for 85% and 70% IR, respectively. In the following season, each tree received 13.04m3 and 10.74m3/year for 85% and 70% IR, respectively. Additionally, there is a total of 57 mm of rainfall each year during both seasons. Two lines of drip irrigation were installed next to the row of trees. Every level of irrigation was allocated to its own row, with two rows running parallel to the tree row. All of water conservations were add at the two furrows (1M wide * 2M long) located on both sides of the trunk of the tree, reaching a depth of 40 cm under the upper soil layer of the emitter in the drip irrigation system. All data collected in the experimental seasons of 2020-2021 and 2021-2022 was conducted using a one-way randomized blocks design, with each treatment being replicated three times, each with three trees.

2.3. Measurements

2.3.1. Vegetative growth parameters

Twenty branches were randomly chosen at March every year from each of the four sides of the tree for the purpose of measuring both vegetation and fruiting parameters. During August, shoot length (cm), number of leaves were counted and leaf area (cm²) was measured in 30 leaves per treatment using the following equation: leaf area = 0.70 (leaf length × leaf width) + 1.06 (Ahmed and Morsy 1999).

2.3.2. leaf physiological parameters

During August from each season, thirty leaves per treatment were used for physiological parameters which include leaf water content (Barrs 1968), chlorophyll concentrations were color-metrically determined using Minolta SPAD-502 (made in Japan). Leaf proline content (mg/g FW) was determined using the ninhydrin reaction (Bates et al., 1973).

2.3.3. Fruiting characteristics

Initial fruit set% was determined on labeled panicle as number of fruitlets per panicle determined two weeks after petal fall (mid of April). Also, final fruit set% was determined by counting number of retained fruits per panicle at harvest (First week of August). Fruit retention at harvest% was determined at harvest as the following equation: Final fruit set/ Initial fruit set X 100

2.3.4. Fruit yield

Number of fruits were estimated by counting the number of fruits per tree at harvest time. Fruit weight was estimated by weighting randomize 30 fruits per tree at harvest time. Yield (Kg) per tree: It was calculated by multiplying the average fruit weight by the number of fruits per tree.

2.3.5. Water use efficiency (WUE)

Water use efficiency (kg m^{-3}) was calculated according to FAO (1982) with the following equation. WUE = Y (kg) / WR (m^3)

where: Y – yield and WR – water requirements

2.3.6. Fruit chemical characteristics

A sample of 15 mature fruits from each replicate tree was taken at the harvest time (Abd El-Razek et al., 2013) for determining the following fruits properties. Fruit weight (kg): It was measured by ordinary balance with 0.01 g sensitivity. Fruit total soluble solids (TSS%): total soluble solids of mango fruit juice were measured using a digital refractometer (A.O.A.C., 1990). The total soluble solids were expressed as a percent. Fruit titratable acidity: Mango fruit juice samples (5 ml) were used and titrated against 0.1 N sodium hydroxide in the presence of phenolphthalein as an indicator (A.O.A.C., 1990). The titratable acidity was expressed as grams of citric acid percent. Ascorbic acid content: was determined as milligrams of ascorbic acid per 100 g Juice with using 2, 6-dichloro phenol indophenol (A.OAC., 1975).

2.4. Statistical analyses

Data obtained from the analytical determinations were subjected to analysis of variance (ANOVA) following the method of Snedecor and Cochran, (1989) using COSTAT software program. The least significant differences (LSD) were employed for comparing treatment means based on Duncan (1955) at a 5% probability level.

3. Results

3.1. Vegetative growth

Figure 1 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the shoot length, number of leaves, and leaf area of Zebda mango tree. Shoot length (cm) is presented in Fig. 1 was affected by the level of irrigation and dose of tested soil conditioners. Reducing water irrigation from 85%IR (T1) to 70%IR (T6) led to a significant decrease in shoot length by 12.86% and 11 % in the first and second seasons, respectively. The highest increase in shoot length recorded by used biochar at 14 Kg/tree (T3) followed by 7 Kg/tree (T2) and hydrogel at 100g/tree (T5) in both seasons at 85%IR. Moreover, both biochar treatment levels resulted in a significant increase in shoot length compared to hydrogel under both 85% and 70% IR.

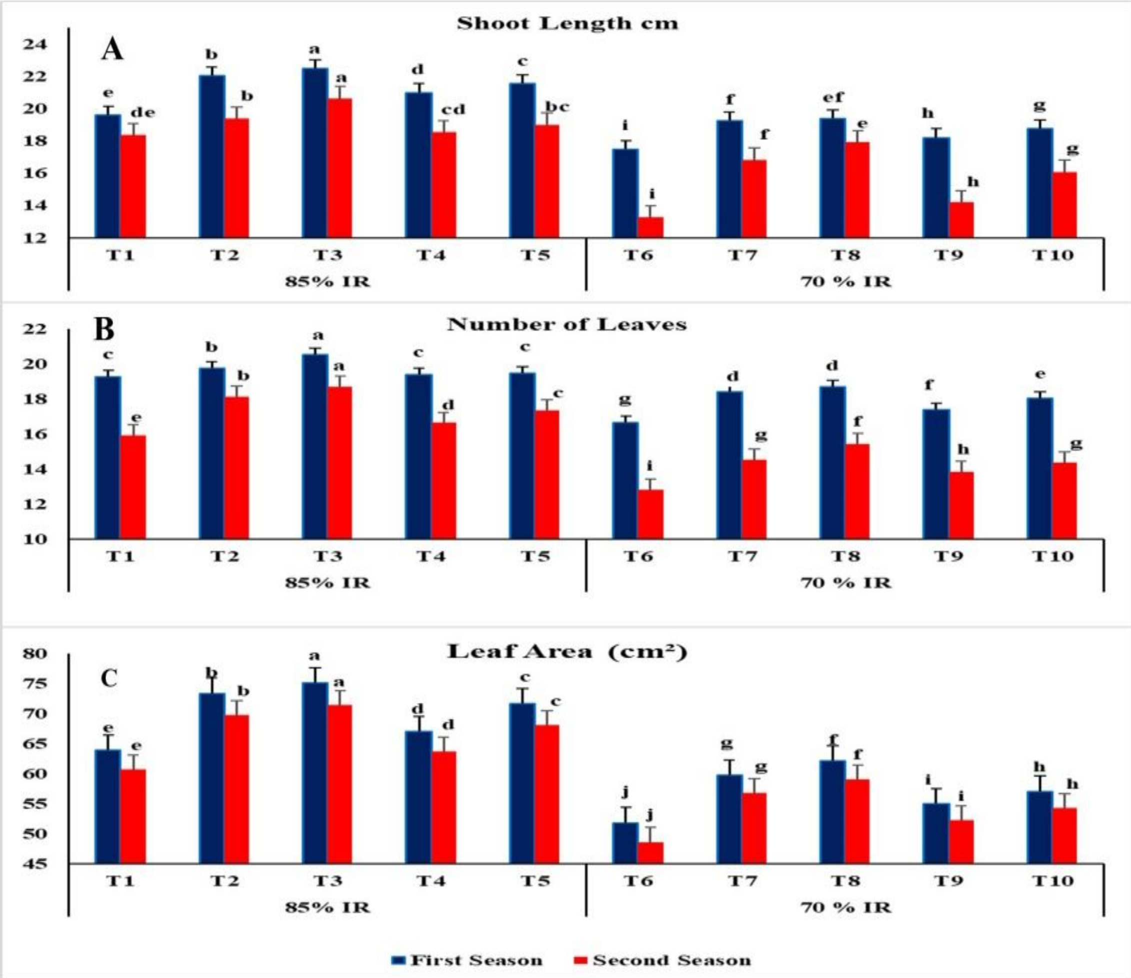

Fig. 1. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the shoot length (A), number of leaves (B) and leaf area (C) of Zebda mango tree. The different treatments include T1 (85%IR), T2 (85%IR+7 kg biochar), T3 (85%IR+14 kg biochar), T4 (85%IR+50 g hydrogel), T5 (85%IR+100 g hydrogel), T6 (70%IR), T7 (70%IR+7 kg biochar), T8 (70%IR+14 kg biochar), T9 (70%IR+50 g hydrogel), and T10 (70%IR+100 g hydrogel). Data were presented as means (n=3±SE).

Reducing water irrigation from 85% to 70%IR significantly decreased number of leaves of Zebda mango trees in both seasons (Fig. 1B). Both hydrogel and biochar applications significantly increased the number of leaves under 85% and 70% IR, except for between hydrogel levels and control at 85% in the first season. Moreover, biochar at 14kg/tree (T3) recorded the highest number of leaves in both seasons with a significant level in the first season compared to all other treatments. While control of IR at 70% IR (T6) recorded the lowest significant values. Decreasing water irrigation from 85% to 70%IR resulted in a significant decrease in the leaf area (Fig. 1C) of Zebda mango trees during both seasons. Both hydrogel and biochar treatments showed a significant increase in leaf area under 85% and 70% deficit irrigation. Moreover, the highest significant values were observed with biochar at 14 kg/tree (T3) and biochar at 7 kg/tree (T2) in comparison to other treatments, followed by hydrogel at 100 g/tree (T5) at 85%IR in both seasons.

3.2. Leaf physiological parameters

Figure 2 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on chlorophyll, proline content and leaf water content of Zebda mango trees. Results in Fig. 2A show deficit irrigation and soil amendments impact the chlorophyll levels of the Zebda mango variety. The chlorophyll content was significantly decreased by reducing water irrigation. Both biochar and hydrogel significantly increased chlorophyll content compared to the control except for 50g hydrogel and control in the second season under 85% IR. Moreover, both biochar levels (T2& T3& T7&T8) showed significantly higher chlorophyll content compared to hydrogel (T4 & T5 & T9 & T10) in both seasons. The highest chlorophyll content was achieved by biochar treatment at 14 kg/tree (T3) followed by biochar at 7 kg/tree (T2) and hydrogel treatment at 100 g/tree (T5) at 85% IR. On the other hand, the lowest chlorophyll content was obtained from 70 IR (T6) without soil amendments.

Data presented in Fig. 2B illustrated the effect of the deficit irrigation and biochar and hydrogel on proline leaves content. Increasing water stress increased proline leaves content. The hydrogel at 100 g/tree recorded the highest proline content in the second season under 70%IR. Water leaf content (WLC) showed a significant decrease as the IR level decreased (Fig. 2C). Biochar at 14 and 7kg (T3, T2) followed by hydrogel at 100g achieved the highest LWC in the second season under 85%IR. While, biochar at 7 kg followed by 14 kg had the highest LWC in both seasons under 70%IR. Water leaf content (WLC) showed a significant decrease as the IR level decreased (Fig. 2C). Biochar at 14 and 7kg (T3, T2) followed by hydrogel at 100g achieved the highest LWC in the second season under 85%IR. While, biochar at 7 kg followed by 14 kg had the highest LWC in both seasons under 70%IR.

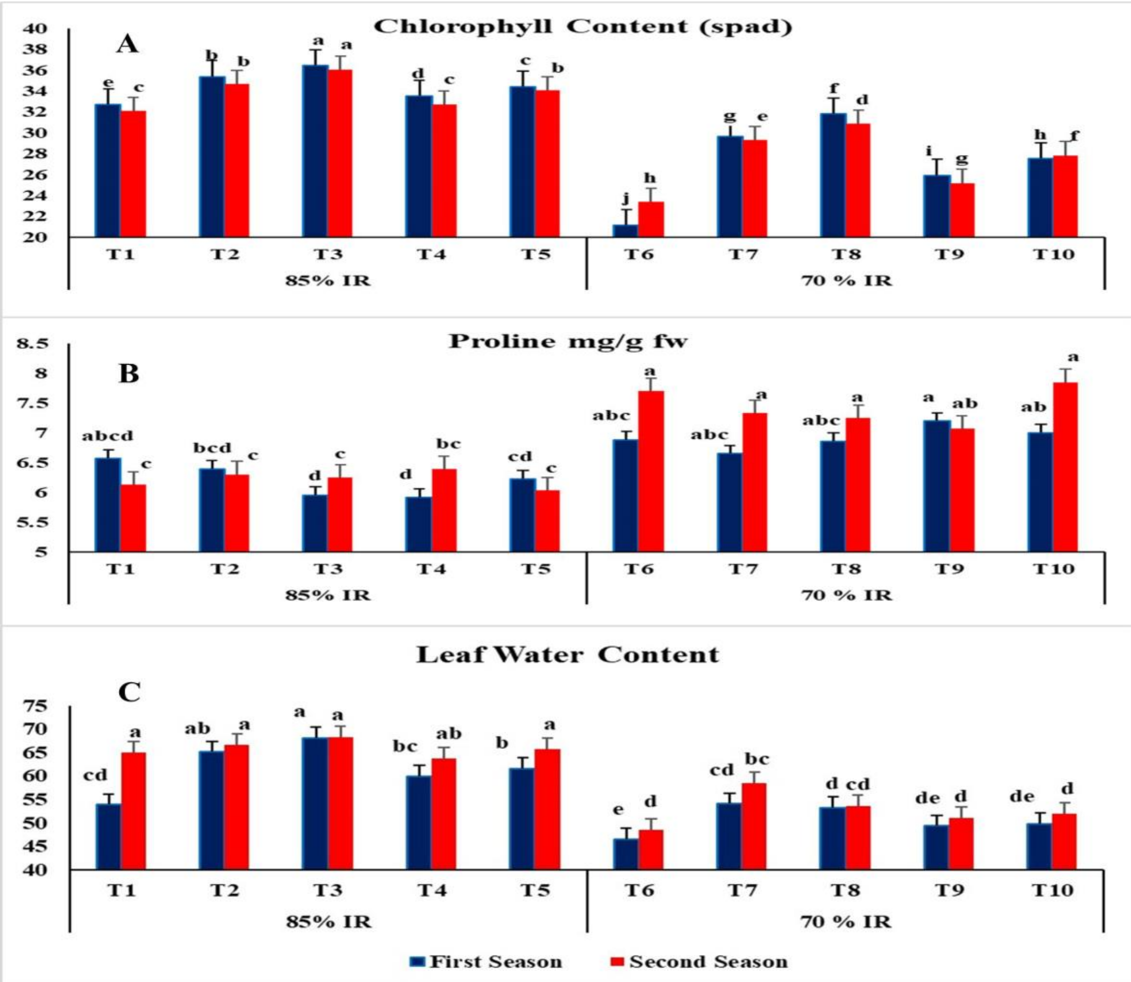

Fig. 2. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on chlorophyll (A) and proline content (B) and leaf water content (C) of Zebda mango trees. The different treatments include T1 (85%IR), T2 (85%IR+7 kg biochar), T3 (85%IR+14 kg biochar), T4 (85%IR+50 g hydrogel), T5 (85%IR+100g hydrogel), T6 (70%IR), T7 (70%IR+7 kg biochar), T8 (70%IR+14 kg biochar), T9 (70%IR+50 g hydrogel), and T10 (70%IR+100 g hydrogel). Data were presented as means (n=3±SE).

3.3. Fruiting characteristics

Figure 3 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the initial fruit set, final fruit set, and fruit retention of Zebda mango tree. Data in Fig. (3A) indicated that reducing irrigation water from 85% to 70% IR resulted in significant lower initial fruit set of Zebda mango fruit in both seasons. But the use of both hydrogel and biochar treatments succeeded in increasing the initial fruit set under 85% & 70% deficit irrigation. Moreover, the highest significant initial fruit set was observed with 14kg/tree of biochar (T3), with 7kg/tree of biochar (T4) closely following in both seasons. Also, hydrogel at 100g / tree (T5) at 85%IR and 70%IR (T10) increased initial fruit set significantly. On contrast, 70% of IR (T6) recorded the lowest values. Decreasing water irrigation from 85% to 70% significantly decreased final fruit set of Zebda mango fruit in both seasons (Fig. 3B). Both treatments with biochar at 7kg (T2&T7) and 14 Kg (T3&T8) and hydrogel at (100 g (T5&T10) significantly increased the final fruit set under 85% & 70% IR deficit irrigation compared to the control (T1& T6) in both seasons. Moreover, biochar at 14 kg/tree (T3) recorded the highest significant final fruit set at 85%IR for both seasons. There is no significant difference between biochar treatments under severe deficit irrigation (70%). Reducing irrigation water from 85% to 70% decreased fruit retention of Zebda mango fruit in both seasons (Fig. 3C). Both of hydrogel and biochar treatments increased the fruit retention under 85% & 70% deficit irrigation. Moreover, used biochar recorded the highest final fruit set for the first and second seasons, respectively.

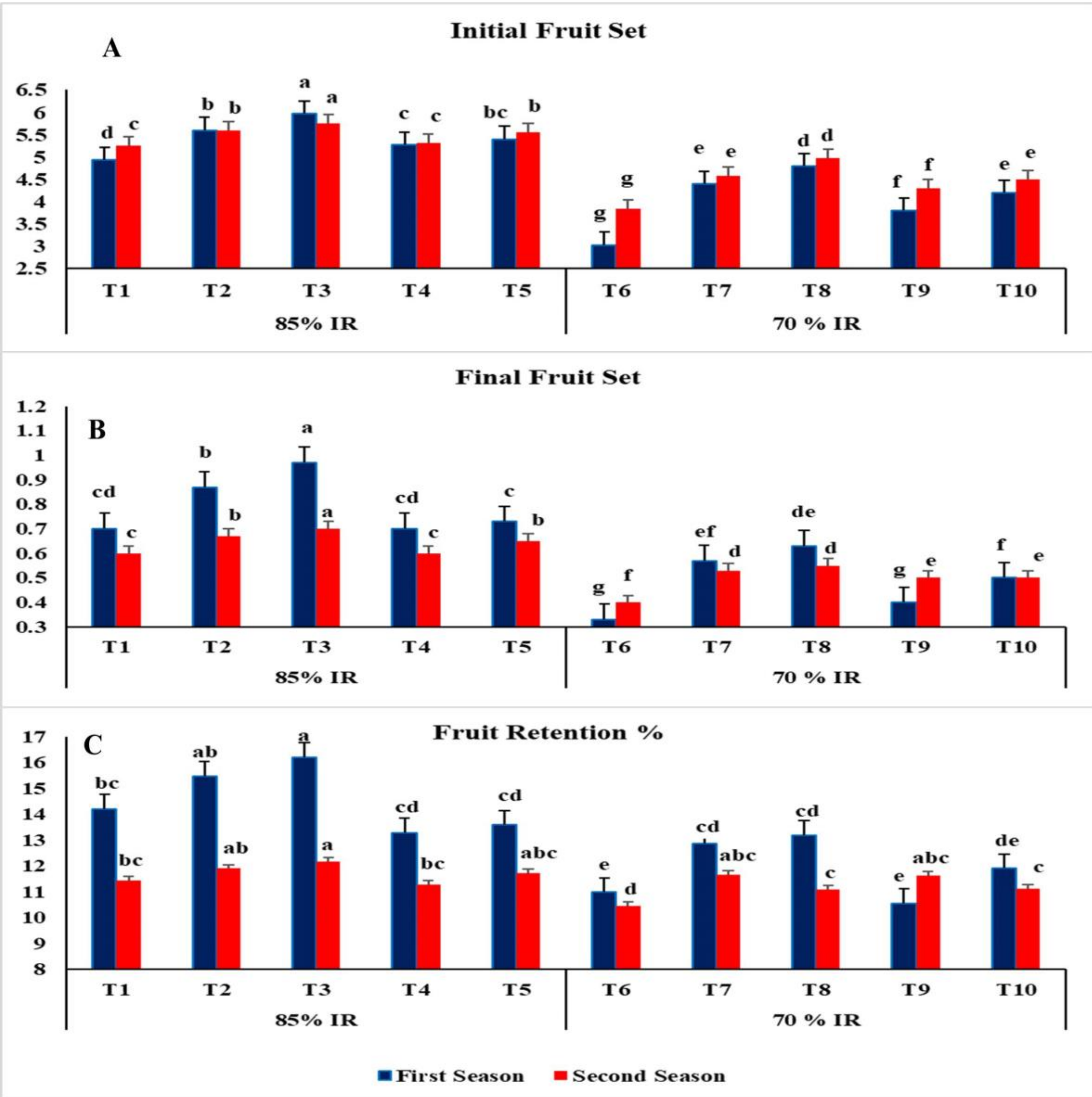

Fig. 3. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the initial fruit set(A), final fruit set(B), and fruit retention (C) of Zebda mango tree. The different treatments include T1(85%IR), T2(85%IR+7 kg biochar), T3 (85%IR+14kg biochar), T4 (85%IR+50g hydrogel), T5(85%IR+100g hydrogel), T6(70%IR), T7(70%IR+7kg biochar), T8 (70%IR+14 kg biochar), T9 (70%IR+50 g hydrogel), and T10 (70%IR+100 g hydrogel). Data were presented as means (n=3±SE).

3.4. Fruit yield

Figure 4 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on fruit number, fruit weight and yield of Zebda mango tree**.** Data presented in Fig. 4A indicated that reducing water irrigation from 85% to 70% led to a significant decrease in the number of fruit per tree of Zebda mango in both seasons. Also, both of hydrogel and biochar treatments increased the number of fruits under 85% & 70% deficit irrigation. Moreover, used biochar at 14 kg/tree (T3), biochar at 7 kg/tree (T2) and hydrogel 100 g/tree (T5) recorded the highest number of fruit/trees at 85%IR in both seasons. Decreasing water irrigation from 85% to 70% significantly decreased fruit weight of Zebda mango fruit (Fig. 4B). Both hydrogel and biochar treatments led to a significant increase in fruit weight under 85% & 70% deficit irrigation except for 50 g/tree hydrogel (T4) in the first season. Moreover, the highest significant fruit weight for the first and second season was recorded by biochar at 14 kg/tree (T3) and biochar at 7 kg/tree (T2) under 85%IR. Reducing irrigation water from 85%IR to 70%IR led to a significant decrease in fruit yield (Fig. 4B) revealed that)per tree of Zebda mango fruit, except for the control in the first season. Both hydrogel and biochar applications led to a significant increase in fruit yield/tree when subjected to 85% and 70% deficit irrigation. Additionally, the highest significant yield for both seasons was observed when using biochar at 14 kg/tree (T3) and biochar at 7 kg/tree (T2) at 85%IR.

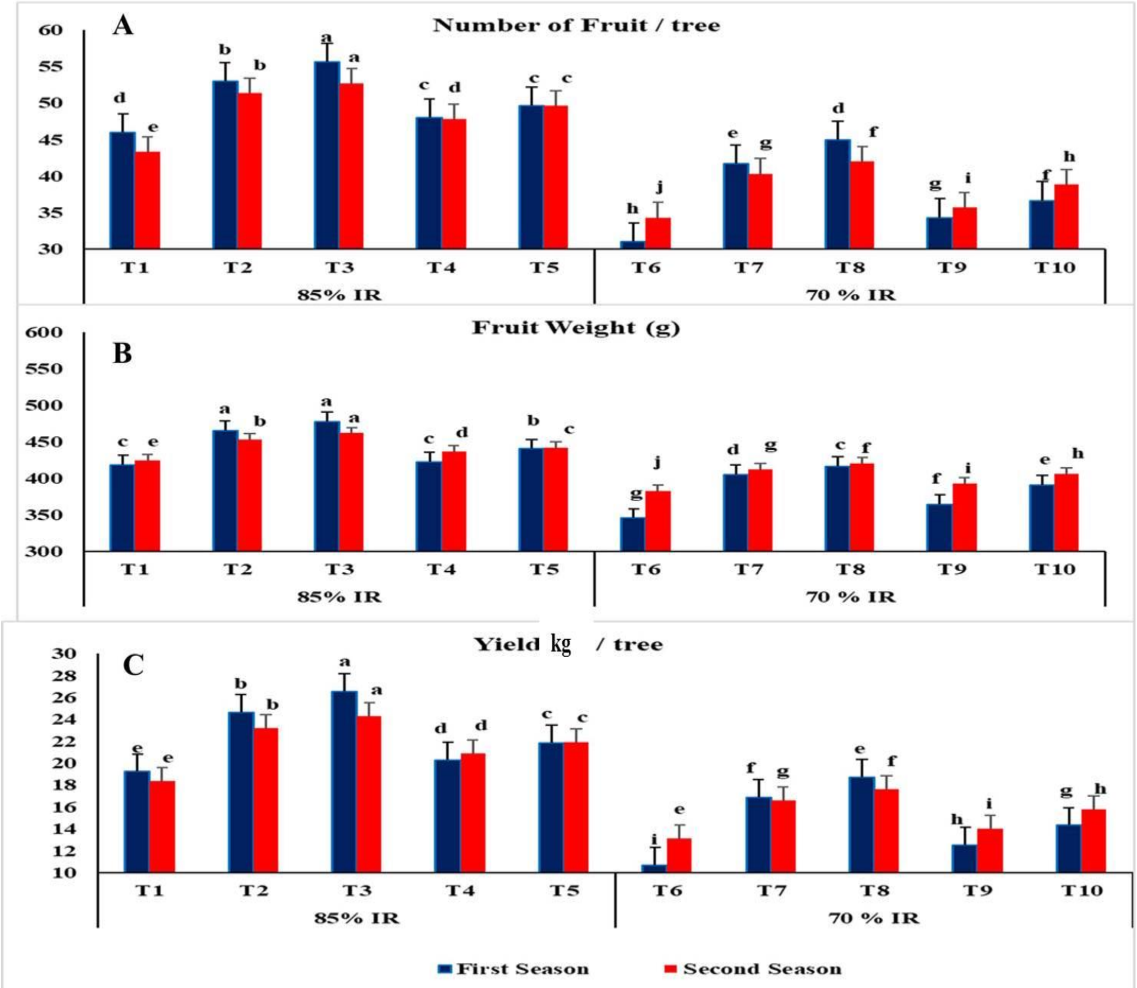

Fig. 4. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on fruit number (A), fruit weight(B) and yield (C) of Zebda mango tree. The different treatments include T1 (85%IR), T2 (85%IR+7 kg biochar), T3 (85%IR+14 kg biochar), T4 (85%IR+50 g hydrogel), T5 (85%IR+100 g hydrogel), T6 (70%IR), T7 (70%IR+7 kg biochar), T8 (70%IR+14 kg biochar), T9 (70%IR+50 g hydrogel), and T10 (70%IR+ 100 g hydrogel). Data were presented as means (n=3±SE).

3.5. Water use efficiency

Figure 5 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on water use efficiency (kg/cm^3) of Zebda mango tree. Decreasing water irrigation from 85% to 70% resulted in a decrease in water use efficiency of Zebda mango trees (Fig. 4) in both seasons, with a significant effect in the second season and between control treatments 0%IR (T1) and 85%IR (T6). Both hydrogel and biochar treatments improved the water use efficiency under 85% & 70% deficit irrigation with a significant values for both soil water conservation in the second season (T7-T8 &T9-T10) as well as with both two level of biochar under 70% IR (T7&T8). Moreover, used biochar at 14 kg/tree (T3) recorded the highest significant water use efficiency compared with control at 85%IR.

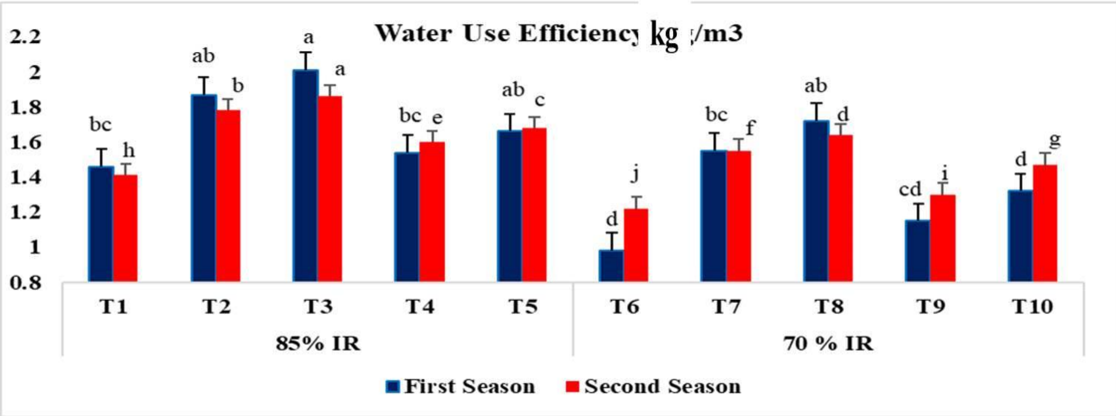

Fig. 5. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on water use efficiency (kg/cm3) of Zebda mango tree. The different treatments include T1 (85%IR), T2 (85%IR+7 kg biochar), T3 (85%IR+14 kg biochar), T4 (85%IR+50 g hydrogel), T5 (85%IR+100 g hydrogel), T6 (70%IR), T7 (70%IR+7kg biochar), T8 (70%IR+14 kg biochar), T9 (70%IR+50 g hydrogel), and T10 (70%IR+100 g hydrogel). Data were presented as means (n=3±SE).

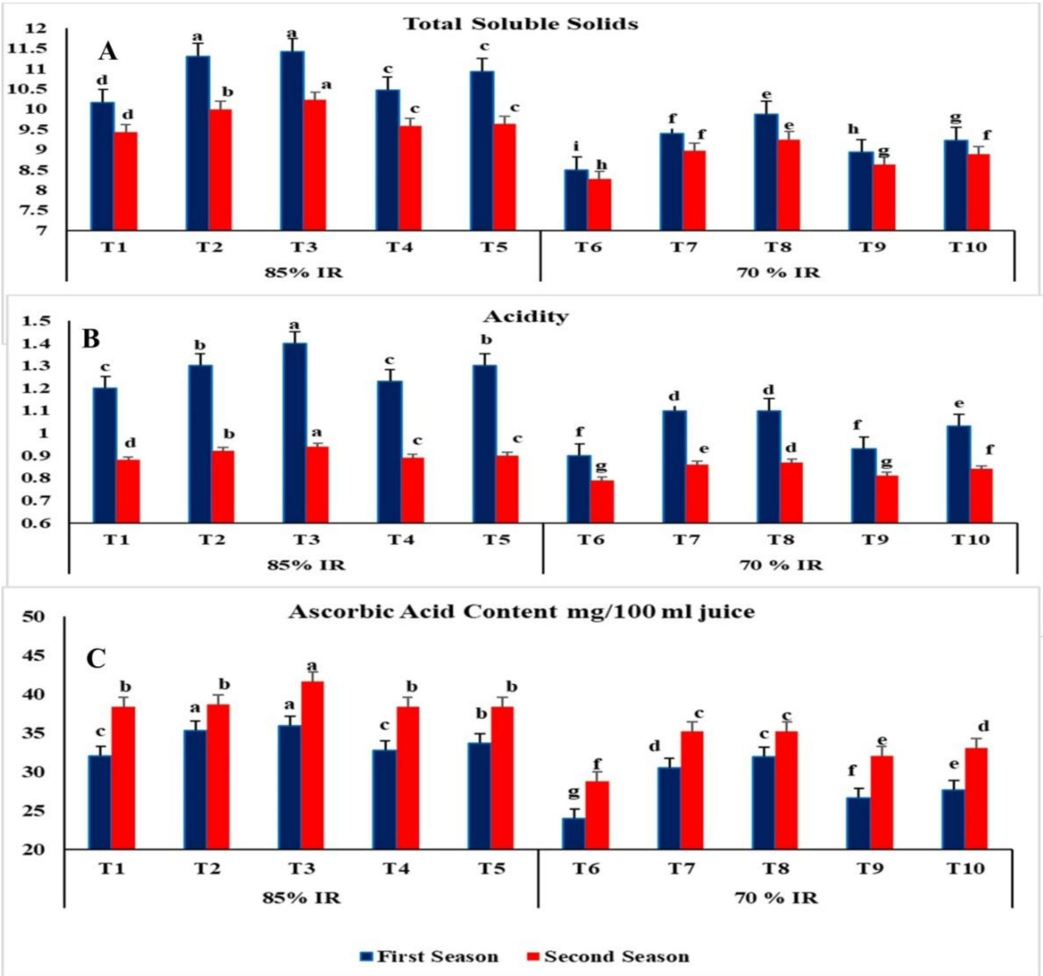

Fig. 6. Effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the Fruit TSS(A), acidity%(B) and ascorbic acid (D) content of Zebda mango fruit. The different treatments include T1 (85%IR), T2 (85%IR+7 kg biochar), T3 (85%IR+ 14 kg biochar), T4 (85%IR+ 50 g hydrogel), T5 (85%IR+ 100 g hydrogel), T6 (70%IR), T7 (70%IR+ 7 kg biochar), T8 (70%IR+ 14 kg biochar), T9 (70%IR+ 50g hydrogel), and T10 (70%IR+ 100 g hydrogel). Data were presented as means (n=3±SE).

3.6. Fruit chemical characteristics

Figure 6 show the effect of two deficit irrigation levels (85% IR and 70%IR) incorporated with biochar or hydrogel, or without soil application, on the Fruit TSS, acidity% and ascorbic acid content of Zebda mango fruit**.** For fruit TSS results in Fig. 5A revealed that, decreasing water irrigation significantly decreased fruit TSS content. Also, biochar and hydrogel succeeded in increasing fruit TSS significantly compared to the two level of deficit irrigation without soil water conservation. Moreover, biochar recorded higher values than hydrogel and the differences between them were significant. The highest value of fruit TSS was recorded by biochar at 14 kg/tree (T3). On the other hand, the deficit irrigation treatments without soil amendments gave the lowest value of fruit TSS (T1&T6) for 85%IR and 70%IR, respectively.

4. Discussion

The findings show that, sever deficit irrigation level at 70%IR reduced vegetative growth compared to moderate deficit irrigation at 85%IR (Fig.1). These results were in agreement with Helaly et al.(2017), showing a decrease in in vegetative growth per spring cycle of 4 mango strains under water stress conditions. Also, Shaban et al. (2021) observed a decrease in the vegetative growth of Keitt mango exposed to 70% IR. This reduction in vegetative growth under water stress conditions may be due to many reasons. First, the formation of reactive oxygen species during water stress damages important cellular components and enzymes inactivation such as and catalase and ascorbate peroxidase (Gong et al., 2008; Munné-Bosch et al., 2013). Second, decreasing of photoassimilate production consume the accumulated amount as well as reduction of photosynthetic pigment and formation of as chlorophyllase which responsible for chlorophyll degradation (Hattori et al., 2008; Almeida et al.,2015). Third, the decrease in nutrient uptake and mineral content and may have accounted for poor vegetative and reproductive growth. (Kour et al., 2022; Abdel-Sattar et al., 2024). Finally, it resulted in decreased growth promoters like cytokinins, gibberellins and auxins in mango leaves whereas, it increased the concentration of growth inhibitors abscisic acid (Helaly et al., 2017).

Meanwhile soil water conservation or amendments were effective in enhancing the growth of Zebda mango trees under 70% and 85% deficit irrigation. This enhancement was furthered by raising the amount of soil amendments. Ghazouani et al. (2023) previously observed that biochar plays a role in enhancing tree growth, with significantly higher levels of catalase and Glutathione found in root content under 0.5% and 1% biochar treatments. Also, Murtaza et al. (2024) who found that, 3% biochar application improve morpho-physiological traits (leaf gas exchange attributes, vegetative growth, rates of transpiration and photosynthesis, leaf relative water content) of tomato plants at levels 60% ETc or 40% ETc. Also, the application of biochar greatly improved both root development and plant growth under drought conditions (Akram, et al., 2024). This could be due to biochar increased porosity and decreased soil dry density which could limit anaerobic root respiration and enhance root activity (Jabborova et al., 2021) and mainly via enhanced antioxidant function (Semida et al., 2019; Amami et al., 2021). Also, hydrogel application improved every aspect of vegetative growth. This could be a result of improving soil water and nutrient intake through the addition of hydrogel. Plants release the nutrients absorbed by hydrogels from the soil in an exchange relationship when they require nutrients for growth (Viruel et al., 2005; Kapłan et al., 2021). Hydrogel succeeded in enhancing growth of olive (Chehab et al., 2017) and mandarin (Kato and Tabi, 2023).

The leaves consider the factory of plant demands for growth and fruiting. The findings showed that a severe deficit irrigation level (70%IR) decreased chlorophyll leaf content. These results were in agreement with those reported on Tommy Atkins mango cv. (Dos Santos, 2014) and Keitt mango cv. (Abdel-Sattar et al., 2024; Shaban et al., 2021). This result could be attributed to a decline in photosynthesis activity (Dos Santos, 2014) causing stomatal closure and transpiration, resulting in limited CO2 assimilation as an adaptation strategy (Taiz & Zeiger, 2009). Moreover, increased chlorophyllase enzyme activity caused by water stress may result in a reduction in chlorophyll levels (Farooq et al., 2009). Furthermore, the decline in chlorophyll content could indicate oxidative stress, photo-oxidation of pigment, and chlorophyll degradation (Abdel-Sattar et al., 2024). On the other side, biochar and hydrogel applications successfully increased chlorophyll levels under deficit irrigation levels. Seleiman et al. (2019) observed an increase in chlorophyll levels in sunflower plants treated with biochar under various deficit irrigation levels (90%, 80%, 75% of FC). This improvement in chlorophyll levels could be a result of biochar enhancing plant growth and physiological functions like stomatal conductance, POX, and CAT activities during water scarcity (Seleiman et al., 2019). Also, plants benefit from improved hydration and increased ability to open stomata with higher water availability(Ma, 2004). Also, hydrogel improved chlorophyll content may be due to enhancing soil water and nutrient intake through the addition of hydrogel for olive trees (Chehab et al., 2017). Plants release the nutrients absorbed by hydrogels from the soil in an exchange relationship when they require nutrients for growth (Viruel et al., 2005; Kapłan et al., 2021).

The findings refer to increase proline production with severe deficit irrigation level (Fig. 2). This results were in line with Elmenofy, et al. (2023) who reported an increase in murcott proline peel content under 70% and 85% ETc . Also, in 4 strains of mango (Abdel-Sattar et al., 2024). This may be attributed to the ability of plants to synthesize and accumulate proline within their cells, facilitating osmotic adjustments that help preserve cellular integrity (Verslues and Sharma, 2010). Also, proline plays a protective role for enzymes by scavenging hydroxyl radicals, thereby preventing enzyme damage (Zafari et al., 2020). Furthermore, it preventing the destruction of the enzyme, hydroxyl radical scavenging, and adjusting osmosis (Zafari et al., 2020). Moreover Proline increase gas exchange and total soluble carbohydrate values, along with a greater internal CO_2 concentration. (da Cunha et al., 2022). Application of biochar decreased proline content under 70%IR. These results are in harmony with those reported by Murtaza et al.(2024) who found that, biochar (3%) reduced proline levels in tomato leaves. Which may be due to the rise in gas exchange and relative water content RWC, along with the decline in proline content, resulted from the growing water availability in the soil which decreased osmotic pressure and improves the plant's ability to absorb water (Inti et al., 2024). While, high level of hydrogel (100 g/tree) succeeded in increasing proline content under sever deficit irrigation level (70%IR). The rise in proline levels due to water scarcity and hydrogel application aligns with previous research results (Abdelghafar et al., 2024). Hydrogel treatment may enhance osmotic protector content by acting as a reservoir in the soil, resulting in a positive impact. This improves crop water intake ability and efficiency, reduces nutrient runoff, enhances fertilizer utilization, and minimizes nutrient loss in sandy soil (Abdelghafar et al., 2024).

Fruit yield is the final product and is a cumulative effect of vegetative, physiological, environmental and nutritional status of plants grown under stress conditions. The findings indicated that sever deficit irrigation decreased fruit set and fruit retention (Fig. 3). These findings were previously reported by Shaban et al.(2021) showing that reducing water irrigation from 85% IR to 70%IR led to decreased fruit retention in Keitt mango cv. Also, severe deficit irrigation decreased fruit set and retention in some mango cultivars such as Chok Anan (L´echaudel and Joas, 2007), Keitt (Abdel-Sattar et al., 2024). Moreover, in Vietnamese, irrigation resulted in a significant increase in fruit retention of Hoi and Tron mango varieties, with a retention rate approximately three times higher than the non-irrigated control (Hagemann et al., 2014). This reduction may be due to water stress prevented nutrient absorption, translocation, and mineral interactions within the plant, ultimately impeding plant growth, development (Sivakumar and Srividhya, 2016). Also, water stress results in the closure of stomata (Campos et al., 2021) due to the release of abscisic acid, which is triggered by the production of abscisic acid, leading to decreased uptake of water and nutrients, as well as fruit drop in plants (Wahdan, 2011). By contrast moderate deficit irrigation at 85% IR maintains high fruit retention percent (Fig. 3C). Similar findings were reported by Abdel-Sattar et al. (2024) showing that moderate irrigation levels of 60-80% significantly increased fruit yield of mango Keitt cv. in Egypt, Guifei mang cv. at 65%-70% IR in China (Wei et al., 2017) and in Chok Anan mango cv. at 80%IR in Thailand (Spreer et al., 2009). Our study showed that soil conservation tools such as biochar and hydrogel succeeded in preserving high fruit set and retention (Fig. 3C) under both 70% and 85% IR. These results could result from improving soil moisture levels, plant growth.

Demonstrating the impact of deficit irrigation on fruit yield by focusing on fruit weight and number (Fig. 4) can assist in determining the optimal stage for implementing regulated deficit irrigation in orchard management. It is evident that deficit irrigation reduced both components with a particularly significant decrease in fruit number. Reducing irrigation requirements from 85 to 70 % decreased number of fruit/trees by 17.37% and 17.73 % and decreased fruit weight by 12.4% and 8% in the first and second season respectively. The yield reduction caused by a reduction in fruit weight at 60%IR (Levin et al. 2015) and in keitt mango at 70-85%IR (Shaban et al., 2021), which resulting from the fact that mango fruits are composed of around 80% water (da Cunha et al., 2022). Also decreasing fruit number decreased fruit yield in keitt mango (Abdel-Sattar et al., 2024; Shaban et al., 2021) at 60%-80%IR, 'Kent' (de Andrade et al., 2024) specially under deficit at 40, 60, 80 ETc, which resulted from decreasing fruit set, fruit retention, growth promoters and vegetative parameters subsequently fruit growth. The high reduction in fruit number during sensitive flowering and fruit set stage come from drop in hot weather, while the reduction is a slight in the weight compared to fruit number, it may be because of how water and growth substances are distributed effectively in the retained fruit, as well as the importance of mature and complete embryos in preventing fruit drop. The reduction in fruit component (number and weight) and yield was linked to high levels of ABA triggered by water stress, leading to fruit drop in early stages of mango development (Schaffer et al., 1994).

Light deficit irrigation may lead to higher fruit production. Since decreasing the necessary water amount to 80% IR positively impacted achieving nearly 100% irrigation in Keitt mango cv. (Abdel-Sattar et al., 2024), guava (Singh et al., 2015) and pomegranate (Intrigliolo et al., 2013). Moreover, de Andrade et al. (2024) recorded that regulated deficit irrigation during flowering stage resulted in increasing fruit number, weight and yield of Kent mango. The rise in production under light or moderate deficit irrigation could be a result of drip irrigation, maintaining consistent soil moisture for active roots, resulting in better nutrient availability and food transport (Singh et al., 2015) or from an increased crop load instead of larger fruit size (Abdel-Sattar et al., 2024) or from reduced competition between plant growth and reproductive organs, with slight water stress lowering organ shedding (Intrigliolo et al., 2013). Regarding the impact of soil conditioners, the findings demonstrate that both biochar and hydrogel successfully increase the number and weight of fruit. Biochar application at 14 Kg/tree with 85% and 70% IR resulted in greater fruit retention by 11.45% & 15.1%, increased fruit weight by 11.45% & 15.1%, higher fruit number by 21.28% & 33.75%, and increased fruit yield by 35.1% & 54.5% respectively. Murtaza et al. (2024) previously observed a rise in fruit production and quality attributed to the use of biochar, with a 3% application leading to increased plant yield in semi-arid and arid areas. Tomato yield increased by 4%, 16%, 8%, and 3% when irrigated with varying levels of freshwater under different water deficit conditions (100% ETc, 80% ETc, 60% ETc, and 40% ETc). The effectiveness of biochar might result from its capacity to hold water, enhance porosity, and provide nutrients to plants in water stress conditions. Also hydrogel increased fruit component and yield . These findings aligned with Alshallash et al.(2022) who reported that, hydrogel led to increased productivity in mango cv. Shelly. Also,increasing yield due to hydrogel application were recorded on olive (Chehab et al., 2017) and mandarin trees (Kato and Tabi, 2023).The positive effect of hydrogel include improving crop yield and characteristics in sandy soils by enhancing water and nutrient retention, leading to increased water and fertilizer use efficiency (Howell, 2001; Abdelghafar et al., 2024). Furthermore, it improves the root-soil environment and establishes a beneficial ecological condition for root growth (Abdallah, 2019), leading to increased nutrient availability and enhanced root absorption and synthesis abilities (Satriani et al., 2018).

Water use efficiency consider the economic environmental products of the agriculture. Reducing irrigation requirements from 85 to 70 % decreased WUE by 27.3 and 24.1 % in the first and second season respectively (Fig. 5). These findings were in harmony with Elmenofy, (2023) who found that murcott trees had higher WUE when grown under 85% ETc compared to 100% ETc. Also, Shaban et al. (2021) observed a rise in WUE in Keitt mango grown under 85% IR than those grown under 100 IR%. Positive impacts of moderate deficit irrigation on root system growth resulted in improved water and nutrient uptake (Xu et al., (2023). Biochar followed by hydrogel specially at high level of application improved greatly WUE. Since biochar at 14 Kg/tree with 85 % and 70 % IR led to increased WUE by 34.7 and 54.9 %, respectively in both seasons. The increase in WUE with 3% biochar was recorded previously by Murtaza et al. (2024) who found increasing WUE of tomato plants subjected to water deficit (80% ETc, 60% ETc, and 40% ETc). Also, increasing WUE was recorded in field crops suchas sugar beet (Yassin et al., 2021), carrot (Abdel-Aziz, 2017) under deficit irrigation. Moreover biochar consider a novel tool, eco-friendly compatible with sustaianable development goals (El-Sherpiny et al., 2023; Singh et al., 2025). The effectiveness of biochar might be attributed to the ability of biochar to hold water, enhance porosity, and supply nutrients to plants in water stress conditions. The increase in WUE with deficit irrigation could be because of reductions in transpiration rate and stomatal closure in response to water stress(Idoudi et al., 2024). Hydrogel application (0, 0.1, 0.2 and 0.3% w/w) improved WUE in lettuce plants grown under (100%, 85%, 70% and 60% of full irrigation requirements), by enhancing plant growth, soil properties, chlorophyll levels, and leaf numbers. The highest water use efficiency was achieved by using hydrogel at 0.3% concentration and supplying 85% of required irrigation, without significantly reducing yield (Abdelghafar et al., 2024). Moreover, increasing WUE were recorded in olive trees under hydrogel application (Chehab et al., 2017).

Fruit chemical properties TSS, acidity and ascorbic acid content. The findings show that, sever deficit irrigation level (70%IR) decreased fruit TSS, acidity and ascorbic acid content (Fig. 6). Reducing irrigation requirements from 85 to 70 % decreased ascorbic acid content by 10.85% and 7.69 % and decreased TSS by 11% and 7.8 % in the first and second seasons, respectively. Reduction of fruit acidity were recorded previously in Murcott fruit under 70% ETc (Elmenofy et al., 2023) and in Keitt mango under 70% and 85% IR (Abdel-Sattar et al., 2024). While, reduction of fruit TSS and ascorbic acid contents disagreed with Abdel-Sattar et al.(2024) who reported that decreasing irrigation levels to 60%IR resulted in improving fruit TSS and ascorbic acid content. Severe deficit irrigation could lead to a decrease in TSS, ascorbic acid content, and acidity due to intense drought stress in hot, arid conditions. Vegetative and fruiting competition in these conditions may result in higher sugar and acid consumption for survival. Additionally, a dilution effect may occur due to the reduction of leaf products (such as sugars and organic acids) in order to reduce stress and survive. Application of biochar and hydrogel successfully improved fruit TSS, ascorbic acid content and acidity content. Biochar at 14 Kg/tree with 85 % and 70 % IR led to increased fruit TSS by 10.43 and 13.98 % and increased ascorbic acid content by 10.25 and 27.6 % respectively. These findings were consistent with Alshallash et al.(2022) who reported an increase in TSS and total sugars of Shelly cv. mango fruit treated with 750g tree. Soil conditioners enhance fruit chemical properties by improving vegetative growth and providing sugars and organic acids, reducing water stress, and ultimately enhancing fruit quality.

5. Conclusions

Decreasing irrigation requirements had a bad effects on mango fruit growth and yield. Biochar and hydrogel, when applied at the highest level, effectively mitigated water stress in mango trees Biochar and hydrogel effectively enhanced chlorophyll content, leaf water retention, fruit set, and both fruit number and weight. Moreover, treatment of 14kg biochar increased fruit yield by 35.1% and 54.5 % as well as improvement in WUE by 34.7% and 54.9% for 85%IR and 70% IR as mean of both seasons. Furthermore, biochar at 14kg surpasses hydrogel at100g by 21.16% and 20.99% in terms of yield and WUE under 70% IR.

List of abbreviations:
IR: irrigation requirements
WUE: water use efficiency
SPAD; Colorimeter indicator of chlorophyll content
TSS: Total soluble sugars
ANOVA: analysis of variance
LSD: least significant differences

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

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