Influence of Deficit Irrigation and Absorbent Materials on "Hass" Avocado Cv.: A- Vegetative Growth, Yield and Fruit Quality.

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ABSTRACT

Avocado (*Persea americana* Mill.) is a globally important fruit crop, with the 'Hass' cultivar being the most widely cultivated. Water scarcity threatens the sustainability of avocado production in arid and semi-arid regions. During (2023–2024) field study was established to evaluate the effects of two soil absorbent materials biopolymer and zeolite applied at 500, 1000, and 1500 g/tree under three regulated deficit irrigation regimes (100%, 80% and 70% of irrigation requirements, IR) on vegetative growth, yield and fruit quality of "Hass" avocado. A split plot design with three replicates was used. Both amendments significantly improved shoot growth, leaf area and relative water content compared to control treatment, particularly under moderate deficit irrigation (80% IR). High dose applications (1500 g/tree) of either biopolymer or zeolite maximized yield (up to 30% over control) under full irrigation, and mitigating yield losses under severe deficit. Fruit quality parameters including weight, size, total leaf carbohydrates content, and oil concentration were consistently enhanced by amendment application. The results demonstrate that integrating high dose water retentive amendments with optimized deficit irrigation can sustain vegetative growth, yield and fruit quality in avocado orchards facing increasing water limitations.

Keywords: *Persea americana* Mill- biopolymer- zeolite- deficit irrigation- vegetative growth.

INTRODUCTION

The global demand for 'Hass' avocado (*Persea americana* Mill.) has surged remarkably over the past few decades due to its exceptional nutritional value and versatile culinary uses (FAOSTAT, 2021 and Whiley and Schaffer, 2018). As a high value subtropical fruit, avocados contribute significantly to the economies of many countries, with the 'Hass' cultivar dominating international markets (Donetti and Terry., 2014 and Araújo et al., 2019). However, avocado cultivation is water intensive, requiring substantial amounts of irrigation to achieve optimal growth and yield (Carr, 2013 and Kassaye et al., 2021). Water scarcity poses a critical challenge to agricultural sustainability; particularly in arid and semi-arid regions where water resources are limited and competition among sectors is intense (Rosegrant et al., 2013 and Mekonnen and Hoekstra, 2016). Climate change exacerbates this issue by altering precipitation patterns and increasing the frequency of droughts (Trenberth et al., 2014). Therefore, improving water use efficiency (WUE) in avocado orchards is essential to ensure productivity while conserving water resources (Fereres and Soriano, 2007 and Padilla-Díaz et al., 2016).One promising strategy to enhance soil water retention and plant water availability involves the incorporation of water absorbent materials into the soil (Abobatta, 2018 and Abrisham et al., 2018).These materials can modify the soil's physical properties, increasing its capacity to retain moisture and nutrients, thereby reducing irrigation frequency and improving WUE (Yang et al., 2014 and Abedi-Koupai and Asadkazemi, 2006). Biopolymers, such as superabsorbent polymers derived from natural sources, have the remarkable ability to absorb and retain large quantities of water relative to their mass, releasing it slowly to plant roots (Hüttermann et al., 2009 and Kabiri et al., 2011). Their application in agriculture has been shown to improve soil structure, enhance seed germination, and increase plant growth and yield under water deficit conditions (Orikiriza et al., 2013 and Guilherme et al., 2015). Zeolite, a microporous aluminosilicate mineral, is valued for its high cation exchange capacity and ability to improve soil fertility and water retention (Mumpton, 1999 and Eberl, 2013). When incorporated into the soil, zeolite can enhance nutrient availability, reduce losses by leaching, and increase WUE, leading to better crop performance (Polat et al., 2004 and Reháková et al., 2004).

Although the individual benefits of these materials are documented, comparative studies evaluating their effects on perennial fruit crops like avocado, particularly under different irrigation regimes, are limited (Abobatta, 2018 and Padilla-Díaz et al., 2016). Understanding how these water absorbent materials interact with varying irrigation levels is crucial for developing efficient water management strategies in avocado cultivation. The outcomes of this research could provide valuable insights for avocado growers facing water scarcity challenges, contributing to sustainable agriculture by enhancing productivity while conserving water resources (Kassaye et al., 2021 and Fereres et al., 2011). Implementing effective water management strategies is essential not only for the economic viability of avocado cultivation but also for environmental conservation in the face of increasing global water demand and climate variability (Rockström et al., 2010 and Foley et al., 2011).

This study aims to investigate the influence of biopolymer and zeolite on the growth, yield, and water use efficiency of 'Hass' avocado trees under three irrigation regimes: 100%, 80%, and 70% of the crop irrigation requirements. By evaluating the performance of these water absorbent materials under full and deficit irrigation conditions, we seek to identify sustainable practices that optimize water use without compromising avocado production.

MATERIALS AND METHODS

Plant materials and study area:

The experiment was performed during 2023–2024 seasons in a commercial avocado orchard located at El-Beheira governorate, Egypt (30.61°N latitude, 30.43°E longitude, and an altitude of 74 m above sea level. The orchard was planted with 10years old Hass avocado trees, uniform in size, vigor, and productivity, spaced at 6.5 × 6.5 meters (100 plant/feddan) on sandy soil. The irrigation system used was drip irrigation, consisting of two lateral lines per tree row, each positioned 50 cm from the trunk on both sides. Emitters were spaced to ensure uniform water distribution across the root zone. The region experiences a long, hot, arid summer and a cool, dry winter, with mean annual temperatures ranging from 8°C to 34.8°C. The climate is suitable for avocado cultivation. All trees were in the full production stage and received standard horticultural practices, including pruning, fertilization, and pest management following the Ministry of Agriculture and Land Reclamation of Egypt recommendations. Soil analysis was performed at depths of 0–90 cm; the soil was classified as sandy, with a water table depth exceeding 1.5 meters, ensuring adequate drainage and root aeration. Detailed soil physical and chemical properties are presented in **Table (1).**

Climate status and irrigation water amount

Average monthly meteorological data of El-Beheira governorate during the 2023 and 2024 growing seasons were obtained from the Borj El Arab International Airport weather station, and are summarized in **Table (2).** Parameters included maximum and minimum temperatures, relative humidity, wind speed, sunshine hours, and reference evapotranspiration (ETo). Monthly irrigation water requirements for each treatment were calculated based on crop evapotranspiration (ETo) and adjusted according to the applied deficit irrigation levels (100%, 80% and 70% of IR). The volume of irrigation water applied per tree during each phenological stage is presented in **Table (3),** reflecting seasonal variation and treatment specific scheduling.

Table (1). Physical and chemical properties of study soil across 0-90 depth profile.

Soil depth (cm)	Soil structure	Sand	Silt (%)	Clay	Bulk density (g/cm³)	CaCO3 (%)	CEC (cmol/kg)	AW (%)	WP (%)	FC (%)	SP (%)
		Physical properties									
0-30	Sandy	87.8	8.6	3.6	1.63	1.80	12.5	4.6	8.0	16.7	3.9
30-60	Sandy	91.2	6.1	2.7	1.55	2.10	11.8	4.4	7.5	16.4	3.5
60-90	Sandy	91.7	5.1	3.2	1.57	2.30	11.2	4.1	7.1	16.2	3.0
Mean	**Sandy**	**90.2**	**6.6**	**3.1**	**1.58**	**2.06**	**11.8**	**4.3**	**7.5**	**16.4**	**3.4**

Soil Fractions: Sand, Silt, Clay.

Chemical properties

Soil depth (cm)	OM (%)	pH	EC (dS/m)	Soluble cations (meq/L) Ca⁺⁺	Mg⁺⁺	Na⁺	K⁺	Soluble nions (meq/L) HCO_3^-	Cl⁻	SO_4^{-2}
0-30	0.18	7.7	0.25	1.25	0.60	0.84	0.12	1.05	1.10	0.20
30-60	0.16	8.0	0.26	1.40	0.64	0.95	0.10	1.20	1.20	0.25
60-90	0.10	8.1	0.28	1.55	0.70	1.00	0.08	1.30	1.35	0.28
Mean	**0.14**	**7.9**	**0.26**	**1.40**	**0.65**	**0.92**	**0.10**	**1.18**	**1.22**	**0.24**

Table (2). Badr city, El-Beheira governorate average monthly calculated meteorological data from of Borj El Arab International Airport (HEBA) weather data during the two growth seasons of 2023 and 2024.

Month	Temperature (C°) Max	Min	Relative humidity %	Wind speed km/h	Sunshine hours	ETo mm/day
			2023			
January	20.3	12	70	12	6.0	14
February	18.3	11	68	14	7.0	14
March	24.6	15	65	15	8.0	15
April	28.1	17	60	14	9.0	14
May	31.3	20	55	16	10.0	16
June	34.0	23	50	14	10.5	14
July	35.8	26	45	13	10.0	13
August	34.5	26	45	14	9.5	14
September	34.6	25	50	14	9.0	14
October	30.0	22	55	13	8.0	13
November	26.6	19	60	13	7.0	13
December	22.3	15	65	14	6.0	14
Average	**28.4**	**19.2**	**57**	**13.7**	**8.3**	**13.7**
			2024			
January	20.1	13	70	13	6.0	13
February	20.8	12	68	15	7.0	15
March	24.3	15	65	14	8.0	14
April	29.6	19	60	15	9.0	15
May	32.1	21	55	14	10.0	14
June	37.2	26	50	14	10.5	14
July	36.6	26	45	12	10.0	12
August	35.7	27	45	12	9.5	12
September	33.8	25	50	12	9.0	12
October	29.3	21	55	15	8.0	15
November	24.1	17	60	13	7.0	13
December	20.8	13	65	14	6.0	14
Average	**28.7**	**19.5**	**57**	**13.5**	**8.3**	**13.5**

Table (3). Monthly irrigation water applied (L/tree) under three irrigation regimes for Hass avocado trees.

Month	Phenological Stage	IR1 (100 %)	IR2 (80 %)	IR3 (70 %)
January	Flower bud formation	60	48	42
February	Floral bud break	90	72	63
March	Flowering to fruit set	91	130	104
April	Fruitlet development	144	126	180
May	Fruit growth	220	176	154
June	Fruit growth	250	200	175
July	Fruit growth	270	216	189
August	Fruit growth	270	216	189
September	Fruit ripening	230	184	161
October	Fruit ripening	160	128	112
November	Flower bud initiation	110	88	77
December	Flower bud initiation	90	72	63
Total (L/tree/year)		**2070**	**1656**	**1451**

Experimental design and applied treatments:

In this experiment, 19 treatments were designed and applied with a total of 57 Hass avocado trees. These treatments were arranged in a split plot design (3 irrigation levels x 2 treatment materials x3 concentrations for each treatment x 3 replicates "trees"). Three regulated deficit irrigation regimes in the main plot were applied which corresponded to 100%, 80%, and 70% of irrigation requirements (IR), and two treatments in three concentrations were arranged in subplots, which were applied as following:

Main plots:

Irrigation treatments:

I1: The optimum amount of irrigation (100%) in the avocado plant in the sandy soil (5110 m^3 /fed/year) (according to Sokkar *et al*., 2022)

I2: Irrigation with 80 % of recommended amount of water (4088 m^3 /fed/year).

I3: Irrigation with 70 % of recommended amount of water (3577m^3 /fed/year).

The deficit irrigation treatments were 80% and 70% of reference irrigation water requirements.

Irrigation was applied at 100%, 80% and 70% of Eto × Kc, calculated according to FAO methodology and validated for avocado under Egyptian conditions (Sokkar et al., 2022).

IR = Kc× ETo× LF × IE × R× Area (fed)/1000

where: IR = Irrigation requirements (m^3 /fed).

Kc = crop coefficient [0.40-0.80] according to Allen et al., (2007).

ETo = reference crop evapotranspiration on (mm/day).

LF = leaching fraction (assumed 20% of irrigation water).

IE = irrigation efficiency of the irrigation system in the field (assumed 85% of the total applied).

R = reduction factor (35-70% canopy cover).

Area = the irrigated area (one feddan = 4200 m^2).

1000 = Conversion factor from liters to cubic meters.

Sub-plots: applied absorbent materials: (according to Kassim et al. (2017) and Khaled et al. (2022).

T1: 0.0 g. (with no applied treatments).

T2: 500 g biopolymer/tree.

T3: 1000 g biopolymer/tree.

T4: 1500 g biopolymer/tree.

T5: 500 g zeolite/tree.

T6: 1000 g zeolite/tree.

T7: 1500 g zeolite/tree.

Study measurements

Vegetative growth: Four labeled branches (at each direction) were taken for vegetative growth measurements including (shoot length (cm), shoot diameter (cm), number of leaves/ shoot, number of shoots /tree) in the last week of August. Leaf area was estimated using the equation given by Ahmed and Morsy (1999); Rojas-Rodríguez *et al*. (2023) were measured and recorded as follows:

Leaf area (cm^2) = 0.70 (leaf length x leaf width) – 1.06

Stomatal conductance (mmol/m²s) was measured on fully expanded mature leaves from the mid-canopy using a portable porometer (SC-1 Leaf Porometer, METER Group, USA). Measurements were taken between 9:00 and 11:00 a.m. under ambient light and temperature conditions to minimize diurnal variation. The sensor head was gently clamped onto the leaf surface, and readings were recorded after stabilization (Tanaka et al., 2013).

Leaf relative water content (RWC) was determined following the method described by Weatherley (1950), with slight modifications. Fully expanded mature leaves were collected from the middle canopy of each tree at midday and immediately weighed to obtain fresh weight (FW). Leaves were then floated in distilled water in darkness at room temperature (20–25 °C) for 24 hours to reach full turgidity, after which turgid weight (TW) was recorded. Subsequently, leaves were oven-dried at 70 °C for 48 hours to determine dry weight (DW). RWC (%) was calculated using the following equation: (RWC) (%) = (FW – DW) (TW – DW)/100

Yield and fruit quality parameters: At commercial harvest, the following yield traits were recorded:

Fruit set (%) calculated as: (Number of fruits/Number of flowers) × 100, according to Drummond (2020).

Yield per tree (kg/tree): Total fruit weight per tree.

Fruit number per tree: Counted manually.

Average fruit weight (g): Mean weight of 20 randomly selected fruits.

Fruit dimensions: Length and width measured using digital calipers; L/D ratio calculated as a shape index.

Fruit total carbohydrates: As described by Dubois et al. (1956).

Fruit total oil content: Oil is extracted from 10 g fresh avocado mesocarp tissue then drying process in oven at 60–70°C, by continuous reflux with petroleum ether in a Soxhlet apparatus. The loss in sample weight after extraction corresponds to the oil content according to Lee (1981).

Statistical analysis:

Data were analyzed using a two-way ANOVA in a split plot design with XLSTAT version 2019.1 (Addi soft, New York, NY, USA). Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. Statistical procedures followed the methods described by Snedecor and Cochran (1980), and differences among means were evaluated using Tukey's HSD at the 5% probability level.

RESULTS

Vegetative growth parameters:

Shoot length:

As it is shown in **Table (4),** shoot length of Hass avocado trees was significantly influenced by both irrigation regimes and absorbent material applications over the two growing seasons. In the first season, shoot length ranged from 21.0 cm in T7 (1500 g zeolite) under the most severe water deficit (IR3) to 33.0 cm in T3 (1000 g biopolymer) under moderate deficit irrigation (IR2). Similar trends were observed in the second season, with all treatments exhibiting a slight increase of approximately 4–6%, reflecting improved plant establishment and soil water interactions. The biopolymer treatments, particularly at 1000 g and 500 g under IR2, produced the longest shoots statistically, while the control and zeolite treatments under IR3 consistently produced the shortest shoots. These results indicate that biopolymer amendments were more effective than zeolite in maintaining shoot elongation under reduced irrigation, with the moderate deficit irrigation (IR2) providing an optimal balance between water availability and physiological growth.

Table (4). Influence of deficit irrigation and absorbent material application on shoot length of Hass avocado trees over two seasons 2023 & 2024.

Treatments materials	Shoot length (cm) – Irrigation Requirements (IR) – IR (1st season) IR1	IR2	IR3	IR (2nd season) IR1	IR2	IR3
T1: 0.0 g (Control)	28.0 ± 1.1 ab	30.0 ± 1.0 a	27.5 ± 1.0 ab	29.0 ± 1.2 ab	31.0 ± 1.0 a	28.5 ± 1.0 ab
T2: 500 g biopolymer	27.0 ± 1.0 ab	32.5 ± 1.0 a	30.0 ± 1.0 a	28.2 ± 1.0 ab	33.8 ± 1.0 a	31.2 ± 1.0 a
T3: 1000 g biopolymer	28.5 ± 1.0 ab	33.0 ± 1.0 a	30.5 ± 1.0 a	29.6 ± 1.1 ab	34.3 ± 1.0 a	31.8 ± 1.0 a
T4: 1500 g biopolymer	25.5 ± 1.0 bc	28.0 ± 1.0 b	26.0 ± 1.0 b	26.6 ± 1.0 bc	29.0 ± 1.0 b	27.1 ± 1.0 b
T5: 500 g zeolite	22.5 ± 0.9 cd	25.0 ± 1.0 bc	23.0 ± 0.9 c	23.5 ± 0.9 cd	26.0 ± 1.0 bc	24.2 ± 0.9 c
T6: 1000 g zeolite	23.5 ± 0.9 c	26.0 ± 0.9 bc	24.0 ± 0.9 bc	24.5 ± 0.9 c	27.0 ± 0.9 bc	25.1 ± 0.9 bc
T7: 1500 g zeolite	21.0 ± 0.8 d	23.0 ± 0.8 c	21.5 ± 0.8 c	22.0 ± 0.8 d	24.0 ± 0.8 c	22.5 ± 0.8 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

Shoot diameter: Shoot diameter followed a trend comparable to shoot length, with significant differences across irrigation regimes and absorbent treatments during both seasons as it is described in **Table (5).** In the first season, the highest diameter was recorded in T3 (1000 g biopolymer) under IR2 at 1.98 cm, while the lowest was observed in T7 (1500 g zeolite) under IR3 at 1.50 cm. The second season exhibited a general increase in diameters, with values reaching up to 2.05 cm for T3 under IR2. Statistical grouping confirmed that biopolymer treatments under moderate irrigation consistently fell into group "a," whereas the control and zeolite under severe deficit were placed in groups "c" and "d." The improvements observed in the second season highlight the role of water-retentive amendments in enhancing cambial activity and stem thickening, thereby contributing to better structural development of avocado trees under partial water deficit.

Table (5). Influence of deficit irrigation and absorbent material application on shoot diameter of Hass avocado trees over two seasons 2023 & 2024.

Treatments materials	Shoot diameter (cm)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	1.85 ± 0.07 ab	2.00 ± 0.06 a	1.90 ± 0.06 ab	1.92 ± 0.07 ab	2.08 ± 0.06 a	1.98 ± 0.06 ab
T2: 500 g biopolymer	1.80 ± 0.07 ab	2.05 ± 0.06 a	1.95 ± 0.06 a	1.87 ± 0.07 ab	2.13 ± 0.06 a	2.02 ± 0.06 a
T3: 1000 g biopolymer	1.82 ± 0.07 ab	2.08 ± 0.06 a	1.98 ± 0.06 a	1.89 ± 0.07 ab	2.16 ± 0.06 a	2.05 ± 0.06 a
T4: 1500 g biopolymer	1.70 ± 0.07 bc	1.85 ± 0.06 b	1.75 ± 0.06 b	1.77 ± 0.07 bc	1.92 ± 0.06 b	1.82 ± 0.06 b
T5: 500 g zeolite	1.55 ± 0.06 cd	1.70 ± 0.06 bc	1.60 ± 0.06 c	1.61 ± 0.06 cd	1.77 ± 0.06 bc	1.66 ± 0.06 c
T6: 1000 g zeolite	1.60 ± 0.06 c	1.75 ± 0.06 bc	1.65 ± 0.06 bc	1.66 ± 0.06 c	1.82 ± 0.06 bc	1.71 ± 0.06 bc
T7: 1500 g zeolite	1.45 ± 0.05 d	1.60 ± 0.05 c	1.50 ± 0.05 c	1.51 ± 0.05 d	1.66 ± 0.05 c	1.56 ± 0.05 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

Leaves number/shoot: Data in **Table (6)** demonstrate that, the number of leaves per shoot during the first season ranged from 17.0 leaves in T7 under IR3 to 26.5 leaves in T3 under IR2, with similar patterns in the second season but with slightly higher values. Biopolymer treatments under moderate deficit (IR2) consistently produced the highest leaf counts, confirming their role in maintaining vegetative activity under limited water conditions. Conversely, zeolite treatments and the nonamended control exhibited significant reductions in leaf number as water availability decreased, indicating their limited capacity to buffer against drought induced leaf abscission. The significant letters show that the treatments with biopolymer were statistically superior to the other treatments, confirming that these materials can maintain leaf retention and promote canopy development under irrigation deficits.

Table (6). Influence of deficit irrigation and absorbent material application on total leaves number of Hass avocado trees over two seasons 2023 & 2024.

Treatments materials	Total leaves number/shoot/tree					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	25.0 ± 1.2 ab	27.0 ± 1.1 a	23.5 ± 1.0 b	26.0 ± 1.2 ab	28.2 ± 1.1 a	24.5 ± 1.0 b
T2: 500 g biopolymer	24.0 ± 1.0 ab	28.5 ± 1.0 a	26.0 ± 1.0 a	25.0 ± 1.0 ab	29.6 ± 1.0 a	27.0 ± 1.0 a
T3: 1000 g biopolymer	24.5 ± 1.0 ab	29.0 ± 1.0 a	26.5 ± 1.0 a	25.5 ± 1.0 ab	30.1 ± 1.0 a	27.5 ± 1.0 a
T4: 1500 g biopolymer	21.0 ± 1.0 bc	23.0 ± 1.0 b	20.5 ± 0.9 b	21.8 ± 1.0 bc	24.0 ± 1.0 b	21.3 ± 0.9 b
T5: 500 g zeolite	19.5 ± 0.9 cd	21.0 ± 1.0 bc	18.0 ± 0.9 c	20.3 ± 0.9 cd	22.0 ± 1.0 bc	18.7 ± 0.9 c
T6: 1000 g zeolite	20.5 ± 0.9 c	22.0 ± 0.9 bc	19.0 ± 0.9 bc	21.3 ± 0.9 c	23.0 ± 0.9 bc	19.8 ± 0.9 bc
T7: 1500 g zeolite	18.0 ± 0.8 d	19.5 ± 0.8 c	17.0 ± 0.8 c	18.7 ± 0.8 d	20.3 ± 0.8 c	17.6 ± 0.8 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

New leaves number/shoot: The production of new leaves per shoot in **Table (7)** reflects current vegetative growth and plant vigor, and it was clearly influenced by the irrigation and amendment treatments in both seasons. In the first season, new leaf formation ranged from 3.5 in T7 under IR3 to 5.3 in T3 under IR2, and these values increased slightly in the second season. Biopolymer applications, particularly at 1000 g, demonstrated the greatest ability to sustain new leaf emergence under moderate deficit irrigation, which is critical for continuous canopy development and photosynthetic activity. In contrast, zeolite and control treatments under severe deficit showed evident suppression of new leaf formation, reflecting higher drought stress. The pattern of statistical significance aligns with the physiological expectation that amendments with higher water holding capacity better support ongoing leaf initiation in partially stressed trees.

Table (7). Influence of deficit irrigation and absorbent material application on leaf total potassium (K) of Hass avocado trees over two seasons 2023 & 2024.

Treatments materials	New leaves no/ Shoot					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	5.0 ± 0.3 ab	6.0 ± 0.3 a	4.5 ± 0.2 b	5.2 ± 0.3 ab	6.2 ± 0.3 a	4.7 ± 0.2 b
T2: 500 g biopolymer	5.5 ± 0.3 ab	6.5 ± 0.3 a	5.0 ± 0.2 a	5.7 ± 0.3 ab	6.8 ± 0.3 a	5.2 ± 0.2 a
T3: 1000 g biopolymer	5.8 ± 0.3 ab	6.8 ± 0.3 a	5.3 ± 0.2 a	6.0 ± 0.3 ab	7.1 ± 0.3 a	5.5 ± 0.2 a
T4: 1500 g biopolymer	4.8 ± 0.2 bc	5.5 ± 0.3 b	4.2 ± 0.2 b	5.0 ± 0.2 bc	5.8 ± 0.3 b	4.4 ± 0.2 b
T5: 500 g zeolite	4.0 ± 0.2 cd	4.5 ± 0.2 bc	3.8 ± 0.2 c	4.2 ± 0.2 cd	4.7 ± 0.2 bc	4.0 ± 0.2 c
T6: 1000 g zeolite	4.3 ± 0.2 c	4.8 ± 0.2 bc	4.0 ± 0.2 bc	4.5 ± 0.2 c	5.0 ± 0.2 bc	4.2 ± 0.2 bc
T7: 1500 g zeolite	3.8 ± 0.2 d	4.2 ± 0.2 c	3.5 ± 0.2 c	3.9 ± 0.2 d	4.4 ± 0.2 c	3.6 ± 0.2 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

Leaf area: Leaf area data in **Table (8)** indicated a marked response to both the level of irrigation and the type of absorbent material used. The largest leaf areas were obtained with T3 (1000 g biopolymer) under IR2, reaching 76.0 cm² in the first season and 79.0 cm² in the second season, whereas the smallest leaves were observed in T7 under IR3 with areas around 55–57 cm². The second season showed modest increases in leaf area for all treatments, indicating a cumulative improvement in water availability and plant acclimation to the applied amendments. Biopolymer treatments clearly enhanced leaf expansion under moderate water deficit, while zeolite and control trees under severe deficit suffered from reduced lamina growth. The statistical letters demonstrate that biopolymer under IR2 was consistently grouped as "a," highlighting its superior capacity to mitigate water stress effects on leaf development.

Table (8). Influence of deficit irrigation and absorbent material application on leaf area (cm^2) of Hass avocado trees over two seasons 2023 & 2024.

Treatments materials	Leaf area (cm^2)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	72.0 ± 3.5 ab	78.0 ± 3.5 a	70.0 ± 3.2 ab	74.8 ± 3.5 ab	81.1 ± 3.5 a	72.8 ± 3.2 ab
T2: 500 g biopolymer	74.0 ± 3.4 ab	80.5 ± 3.4 a	75.0 ± 3.3 a	76.9 ± 3.4 ab	83.7 ± 3.4 a	78.0 ± 3.3 a
T3: 1000 g biopolymer	75.0 ± 3.3 ab	82.0 ± 3.3 a	76.0 ± 3.3 a	78.0 ± 3.3 ab	85.3 ± 3.3 a	79.0 ± 3.3 a
T4: 1500 g biopolymer	68.0 ± 3.2 bc	70.0 ± 3.2 b	65.0 ± 3.0 b	70.7 ± 3.2 bc	73.0 ± 3.2 b	67.6 ± 3.0 b
T5: 500 g zeolite	60.0 ± 3.0 cd	63.0 ± 3.0 bc	58.0 ± 2.9 c	62.4 ± 3.0 cd	65.5 ± 3.0 bc	60.3 ± 2.9 c
T6: 1000 g zeolite	62.0 ± 3.0 c	65.0 ± 3.0 bc	60.0 ± 2.9 bc	64.5 ± 3.0 c	67.6 ± 3.0 bc	62.4 ± 2.9 bc
T7: 1500 g zeolite	58.0 ± 2.8 d	60.0 ± 2.8 c	55.0 ± 2.8 c	60.3 ± 2.8 d	62.4 ± 2.8 c	57.2 ± 2.8 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

Stomatal conductance: Stomatal conductance, a key physiological indicator of water status and photosynthetic potential, was significantly affected by irrigation level and treatments type as it is presented in **Table (9).** In the first season, stomatal conductance (g) ranged from 160 mmol/m²s in T7 under IR3 to 225 mmol/m²s in T3 under IR2, with all values increasing slightly in the second season. Biopolymer treated trees maintained higher conductance (g) across all irrigation regimes, especially under IR2, suggesting improved stomatal regulation and enhanced gas exchange despite moderate water deficit. Severe deficit (IR3) caused substantial declines in stomatal conductance across all treatments, but the negative impact was more pronounced in zeolite and nonamended trees. Statistical analysis indicates that T3 under IR2 was significantly superior to other treatments, and the second season increases suggest that cumulative amendment effects improved soil moisture availability and plant water relations over time.

Table (9). Influence of deficit irrigation and absorbent material application on leaf stomatal conductance of Hass avocado trees over two seasons 2023 & 2024.

	Stomatal conductance (gs) (mmol/m²s)					
Treatments materials	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	**IR2**	**IR3**	**IR1**	**IR2**	**IR3**
T1: 0.0 g (Control)	210 ± 10 ab	230 ± 10 a	200 ± 9 ab	218 ± 10 ab	239 ± 10 a	208 ± 9 ab
T2: 500 g biopolymer	215 ± 9 ab	240 ± 10 a	220 ± 9 a	224 ± 9 ab	250 ± 10 a	229 ± 9 a
T3: 1000 g biopolymer	220 ± 9 ab	245 ± 10 a	225 ± 9 a	229 ± 9 ab	255 ± 10 a	234 ± 9 a
T4: 1500 g biopolymer	200 ± 9 bc	210 ± 9 b	190 ± 9 b	208 ± 9 bc	218 ± 9 b	197 ± 9 b
T5: 500 g zeolite	180 ± 8 cd	190 ± 8 bc	170 ± 8 c	187 ± 8 cd	197 ± 8 bc	177 ± 8 c
T6: 1000 g zeolite	185 ± 8 c	195 ± 8 bc	175 ± 8 bc	192 ± 8 c	203 ± 8 bc	182 ± 8 bc
T7: 1500 g zeolite	170 ± 8 d	180 ± 8 c	160 ± 8 c	177 ± 8 d	187 ± 8 c	166 ± 8 c

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at p ≤ 0.05.

Leaf relative water content: Deficit irrigation sharply lowered leaf RWC as it's shown in **Table (10),** especially under IR3 (control: 63.1 % in 2023, 65.0 % in 2024). Biopolymer at 1500 g (T4) sustained the highest RWC across all IR regimes (80.6 % under IR3 in 2023; 82.5 % in 2024), reflecting a 17 – 18 % gain over control. Zeolite at 1500 g (T7) achieved similar improvements (78.6 % and 80.5 %), significantly outperforming lower doses ($p \leq 0.05$).

Table (10). Influence of deficit irrigation and absorbent material application on relative water content (RWC) % of Hass avocado trees over two seasons 2023 & 2024.

	Relative water content (RWC) %					
Treatments materials	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	**IR2**	**IR3**	**IR1**	**IR2**	**IR3**
T1: 0.0 g (Control)	84.5 ± 0.8 f	75.2 ± 1.0 f	63.1 ± 1.2 f	86.0 ± 0.7 f	78.3 ± 0.8 f	65.0 ± 0.8 f
T2: 500 g biopolymer	87.0 ± 0.7 e	78.0 ± 0.9 e	67.5 ± 1.0 e	88.0 ± 0.8 e	80.5 ± 0.8 e	69.8 ± 0.9 e
T3: 1000 g biopolymer	90.5 ± 1.0 c	83.0 ± 1.1 c	75.2 ± 0.8 c	91.2 ± 0.8 c	84.5 ± 0.9 c	77.0 ± 0.9 c
T4: 1500 g biopolymer	92.3 ± 0.8 a	87.5 ± 1.0 a	80.6 ± 0.7 a	93.5 ± 0.8 a	88.5 ± 0.9 a	82.5 ± 0.8 a
T5: 500 g zeolite	88.0 ± 0.9 d	80.0 ± 1.0 d	70.8 ± 0.9 d	89.0 ± 0.9 d	82.0 ± 0.9 d	72.5 ± 0.9 d
T6: 1000 g zeolite	91.0 ± 0.8 b	85.2 ± 0.9 b	77.1 ± 0.8 b	92.0 ± 0.9 b	87.3 ± 0.8 b	79.2 ± 0.8 b
T7: 1500 g zeolite	91.8 ± 0.8 ab	86.2 ± 0.9 ab	78.6 ± 0.7 ab	92.8 ± 0.7 ab	88.0 ± 0.8 ab	80.5 ± 0.9 ab

Means within each season followed by the same letter are not significantly different according to Tukey's HSD test at p ≤ 0.05.

Yield and fruit quality:

Fruit set percentage:

Fruit set percentage of Hass avocado during the two seasons was significantly influenced by the interaction of irrigation regime and absorbent material type and dosage across both seasons **(Fig. 1).** The control treatment (T1) consistently recorded the lowest fruit set under all irrigation levels, especially under IR3, where percentages fell below 45% in the first season and under 40% in the second season. Conversely, T4 and T7 representing 1500 g of biopolymer and zeolite respectively under full irrigation (IR1) conditions repeatedly yielded the highest fruit set percentages, exceeding 85% and 80% in the first and second seasons respectively. These treatments were consistently categorized within statistical group “a”, highlighting their superior role in enhancing fruit retention and ovary development under optimal water supply. Intermediate treatments (T2–T6) demonstrated dose responsive improvements in fruit set, with values ranging between 55% and 75%. Variability in performance was attributed to both material type and irrigation severity.

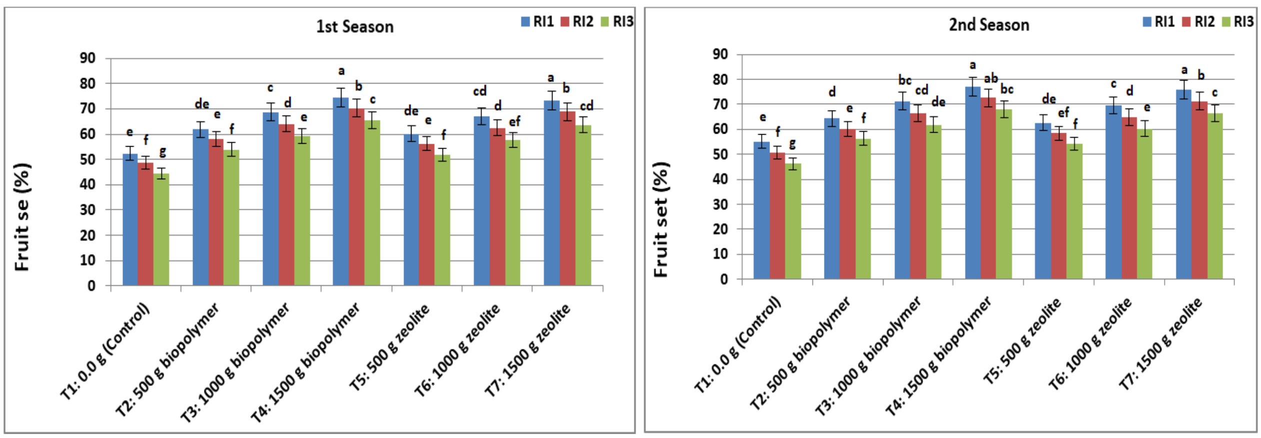

Fig. (1). Influence of deficit irrigation and absorbent material application on fruit set (%) of Hass avocado tree over 2023 and 2024 seasons.

Yield: Data of both seasons revealed that, irrigation levels and absorbent materials applications significantly affected fruit yield **(Fig. 2).** Across both years, trees receiving full irrigation (100%) produced the highest yields, which were further enhanced by the addition of absorbent material. Specifically, biopolymer amended trees yielded 24.3 kg and 26.1 kg/tree in 2023 and 2024, respectively, while unamended controls under the same irrigation treatment produced slightly lower yields of 22.8 kg and 24.7 kg/tree. Under moderate deficit irrigation (80%), yields declined in both years; however, the negative impact was substantially mitigated by the use of absorbent material. In 2023, amended trees produced 21.7 kg/tree compared to 18.5 kg/tree in controls, while in 2024 yields were 23.4 kg and 20.2 kg/tree, respectively. Severe water stress (70%) led to the lowest overall yields, yet absorbent application still conferred notable benefits. Trees treated with absorbent material yielded 17.9 kg and 19.5 kg/tree across both seasons, respectively, compared to 14.2 kg and 15.8 kg/tree for unamended trees.

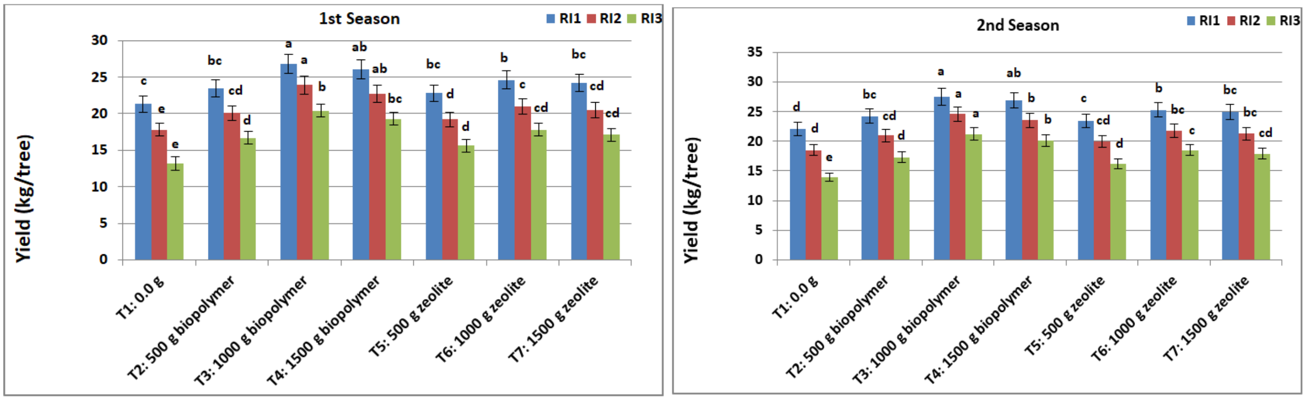

Fig. (2). Influence of deficit irrigation and absorbent material application on yield (kg)/tree of Hass avocado tree over 2023 and 2024 seasons.

Fruit number/tree: Fruit number per Hass avocado tree was consistently and significantly influenced by irrigation regime and the type and dosage of absorbent materials applied over both growing seasons **(Fig. 3).** The control treatment (T1) under IR3 (severe deficit irrigation) recorded the poorest performance, with fruit counts falling below 60 fruits per tree in the first season and further declining to under 55 fruits in the second. In contrast, treatments T4 and T7 corresponding to 1500 g of biopolymer and zeolite respectively under full irrigation (IR1) achieved the highest fruit yields in both seasons. Fruit numbers surpassed 210 fruits per tree in 2023 and 250 fruits per tree in 2024. This underscores their pronounced efficacy in improving fruit retention, ovary development, and overall reproductive success under adequate soil moisture. Intermediate treatments (T2–T3 for biopolymer; T5–T6 for zeolite) exhibited moderate fruit numbers ranging from 110 to 220 fruits per tree, depending on material dose and irrigation level.

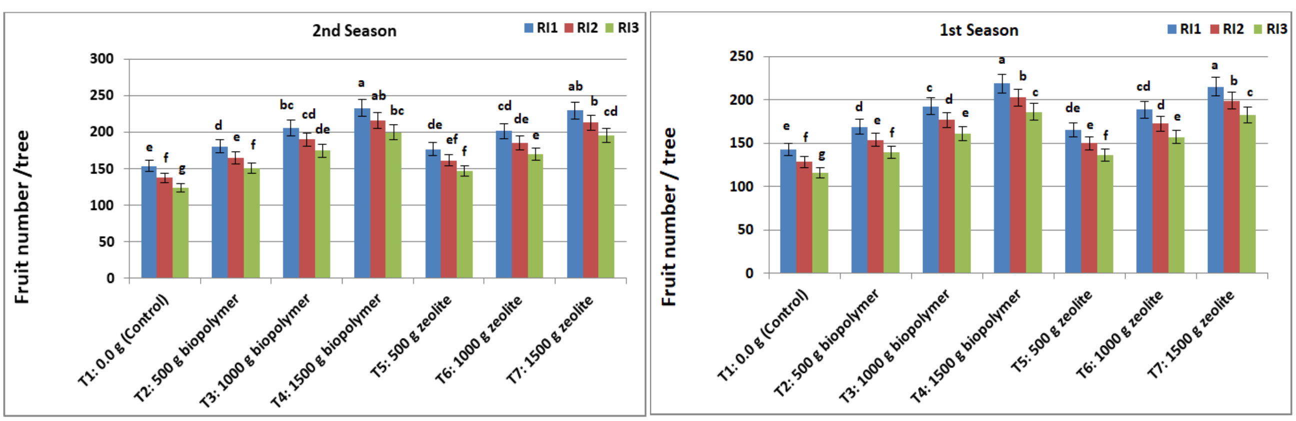

Fig. (3). Influence of deficit irrigation and absorbent material application on fruit number /tree of Hass avocado tree over 2023 and 2024 seasons.

Fruit weight:

Fruit weight of Hass avocado exhibited a significant response to both irrigation regimes and absorbent material applications across both seasons **(Fig. 4).** Under full irrigation (100%), trees consistently produced the highest fruit weights, especially when absorbent materials were applied.

In the first season, fruit weight ranged from 217.4 g under severe deficit irrigation (70%) without amendments (T1) to 263.7 g under full irrigation with 1500 g biopolymer (T4).

Application of biopolymer or zeolite at all levels generally improved fruit weight across irrigation treatments, with higher doses (1000 –1500 g) showing more pronounced effects. Statistical comparisons revealed distinct groupings, with amended treatments under 100% IR significantly outperforming lower irrigation levels and controls. In the second season, a similar pattern was observed, with absolute fruit weights slightly elevated, likely due to tree maturity and enhanced nutrient assimilation. The highest fruit weight (274.3 g) was recorded in T4 (1500 g biopolymer under 100% IR), followed by T7 (1500 g zeolite, 273.1g). Control trees under 70% IR yielded the lowest fruit weight (224.6 g). Significance letters revealed improved differentiation among treatments compared to the first season, suggesting more robust performance and enhanced sensitivity to amendment effects as trees developed.

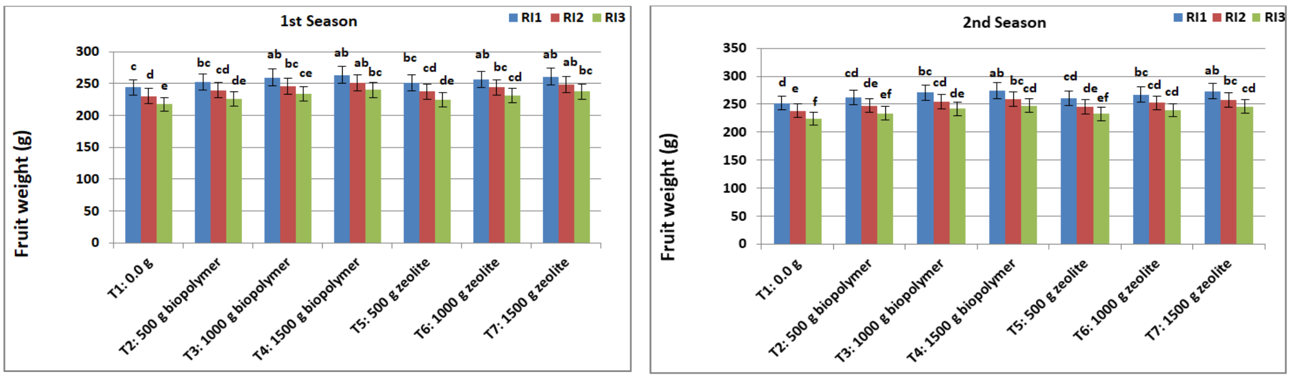

Fig. (4). Influence of deficit irrigation and absorbent material application on fruit weight (g) of Hass avocado tree over 2023 and 2024 seasons.

Fruit length: Fruit length was significantly influenced by the interaction of irrigation regime and absorbent material dose during both seasons **(Fig. 5).** In the first season, treatments T4 and T7 applying 1500 g biopolymer and zeolite respectively under full irrigation (IR1) recorded the highest fruit lengths, reaching 10.6 cm and 10.4 cm, respectively. Control treatment T1 under deficit irrigation (IR3) registered the shortest length of 8.2 cm. Intermediate treatments under moderate irrigation (IR2) showed gradual increases with dose escalation, forming distinct statistical groupings. In the second season, trends remained consistent. T4 and T7 under IR1 produced maximal fruit lengths of 10.8 cm and 10.7 cm. The control treatment under IR3 remained the lowest at 8.4 cm. Moderate improvements were seen in IR2 treatments, particularly with higher amendment doses.

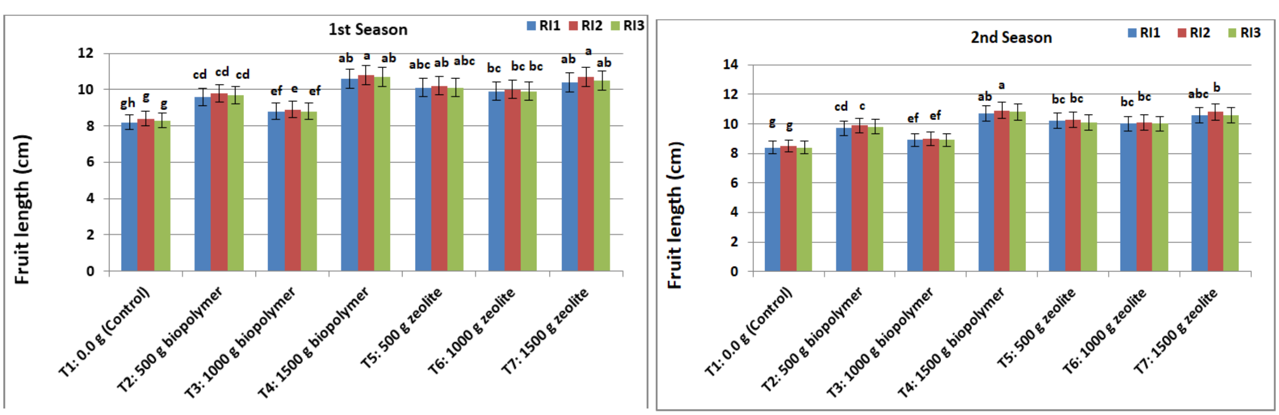

Fig. (5). Influence of deficit irrigation and absorbent material application on fruit length (cm) of Hass avocado tree over 2023 and 2024 seasons.

Fruit width: Fruit width of Hass avocado exhibited significant variation in response to irrigation regime and absorbent material application across both seasons **(Fig. 6).** In the first season, the highest fruit widths were observed under full irrigation (IR1) combined with high dose amendment treatments. Specifically, T4 and T7 1500 g biopolymer and zeolite respectively yielded widths of 8.3 cm and 8.1 cm. Conversely, the control treatment (T1) under IR3 presented the lowest fruit width at 6.5 cm. Treatments with lower amendment doses and intermediate irrigation levels (IR2) showed moderate improvements ranging between 7.4–7.9 cm. During the second season, these trends were largely consistent. T4 and T7 under IR1 again recorded superior fruit widths of 8.5 cm and 8.4 cm. The control treatment under IR3 remained the least effective, registering 6.6 cm. Notably, intermediate treatments showed slight shifts in statistical groupings, with T2 and T5 under IR2 displaying enhanced performance relative to their first season counterparts.

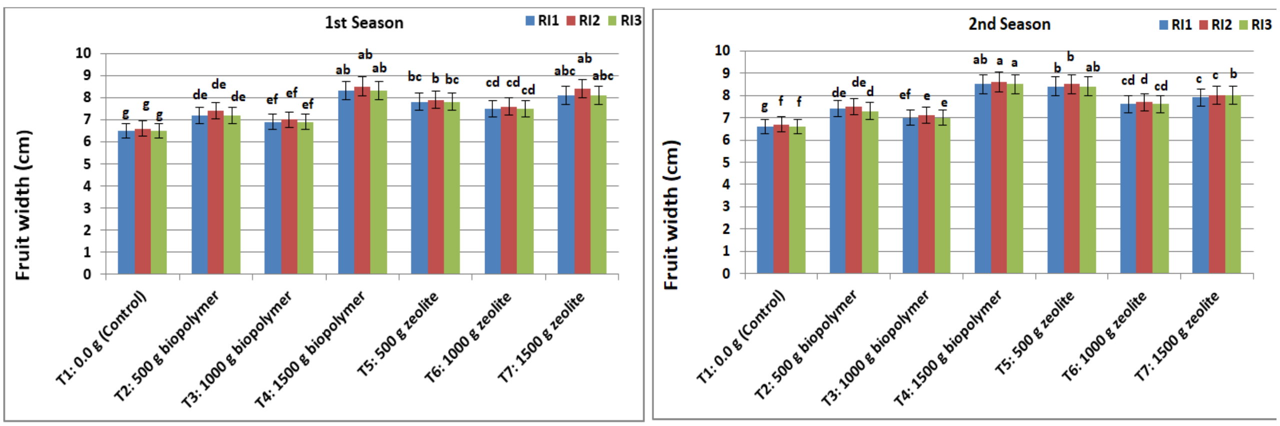

Fig. (6). Influence of deficit irrigation and absorbent material application on fruit width (cm) of Hass avocado tree over 2023 and 2024 seasons.

Fruit shape index (D/L ratio): Fruit shape index of Hass avocado was significantly influenced by both irrigation regime and the application rate and type of absorbent material in both seasons **(Fig. 7).** In the first season, the highest D/L ratios were recorded in T4 (1500 g biopolymer) and T7 (1500 g zeolite) under full irrigation (IR1), reaching 0.85 and 0.84, respectively. These were followed closely by T3 and T6 at moderate doses under IR1. The lowest shape index was observed in the control (T1) under severe deficit irrigation (IR3) at 0.74, indicating more elongated fruits under water stress without amendments. Intermediate treatments (T2, T5), reflecting a dose dependent improvement across irrigation levels. In the second season, trends were consistent, though values increased slightly across most treatments. T4 and T7 under IR1 again recorded the highest ratios (0.87 and 0.86), while T1 under IR3 remained the lowest at 0.75. Moderate irrigation (IR2) treatments displayed statistically intermediate ratios, with T4 and T7 outperforming other materials at equivalent doses. Minor shifts in significance groupings were noted between seasons, but the ranking of top and bottom performers remained stable. Overall, high dose biopolymer or zeolite under full irrigation consistently produced more rounded fruit shapes (higher D/L ratio), while severe irrigation deficit without amendments promoted more elongated forms.

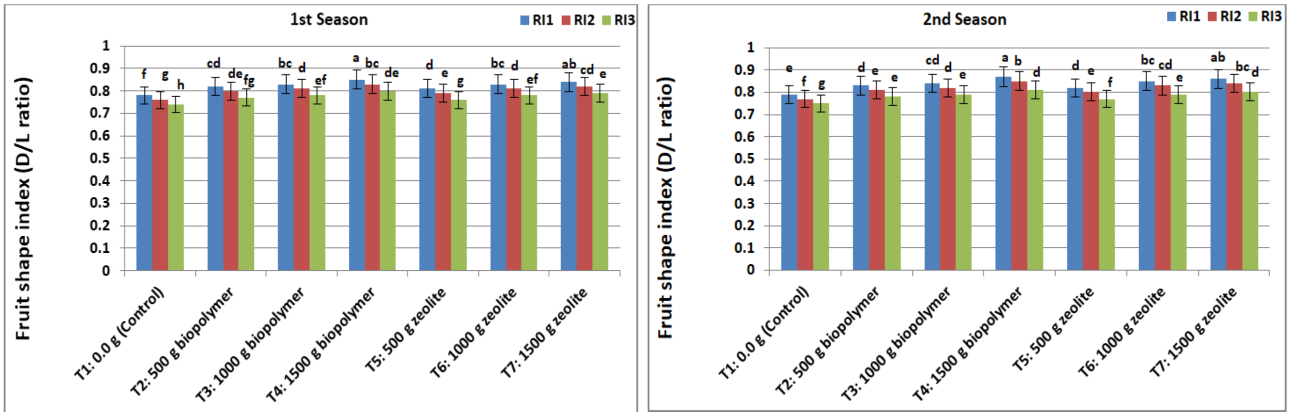

Fig. (7). Influence of deficit irrigation and absorbent material application on fruit shape index (D/L ratio) of Hass avocado tree over 2023 and 2024 seasons.

Fruit total carbohydrates:

Fruit total carbohydrate concentration was significantly affected by both irrigation regime and type/dose of absorbent material during the two study seasons. In the first season **(Fig. 8),** the highest carbohydrate levels were recorded in T4 (1500 g biopolymer) and T7 (1500 g zeolite) under full irrigation (IR1), reaching 15.4% and 15.2%, respectively. These were followed closely by T3 and T6 under IR1 (14.8–15.0%). Moderate irrigation (IR2) with high dose amendments (T4, T7) maintained significantly higher carbohydrate levels (14.6%) than low dose treatments or the control. Severe deficit irrigation (IR3) without amendment (T1) produced the lowest values (12.0%), indicating strong carbohydrate depletion under combined stress. According to data in **(Fig. 8),** a similar trend was observed in the second season, with slight increases across most treatments. T4 and T7 under IR1 again dominated (15.7% and 15.5%), while the IR3 control remained the lowest (12.3%). Notably, IR2 with high dose biopolymer or zeolite showed improved carbohydrate retention compared with the previous season, suggesting some cumulative benefit of amendment use. Generally, the results indicate that maximizing fruit carbohydrate content in Hass avocado requires combining optimal irrigation with high dose absorbent material, with biopolymer and zeolite showing comparable efficacy. Severe water deficit without amendment consistently resulted in the lowest carbohydrate accumulation in both seasons.

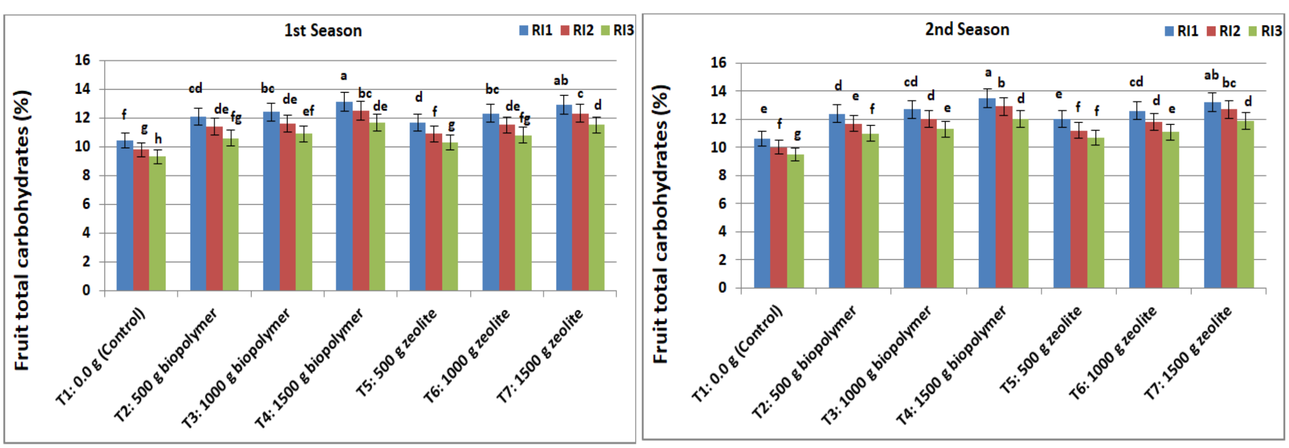

Fig. (8). Influence of deficit irrigation and absorbent material application on fruit total carbohydrates (%) of Hass avocado tree over 2023 and 2024 seasons.

Fruit total oil content:

Fruit total oil content of Hass avocado was significantly influenced by irrigation regime and the type and application rate of absorbent materials across both seasons. According to data in **(Fig. 9),** the first season, the highest oil percentages were achieved by T4 (1500 g biopolymer) and T7 (1500 g zeolite) under full irrigation (IR1), recording 12.4% and 12.1%, respectively. These were closely followed by T3 and T6 at 1000 g doses under IR1, which also produced oil levels exceeding 11.5%. In contrast, the control (T1) under severe deficit irrigation (IR3) exhibited the lowest oil content at 8.7%, indicating substantial reduction under combined water stress and absence of soil amendments. Intermediate treatments under moderate irrigation (IR2) yielded oil contents in the range of 10.5–11.7%, with statistical separation reflecting both dose and material effects. In the second season **(Fig. 9),** the treatment ranking remained consistent, though values increased slightly across most combinations. T4 and T7 under IR1 maintained their superiority at 12.7% and 12.5%, while the IR3 control persisted as the lowest at 8.8%. Moderate irrigation with high dose amendments again demonstrated a significant advantage over lower doses or untreated controls, suggesting improved oil biosynthesis under adequate or partially restricted water supply when paired with absorbent materials. The data highlight a clear, dose dependent enhancement of fruit oil concentration in response to biopolymer and zeolite applications, with maximum benefits achieved under full irrigation.

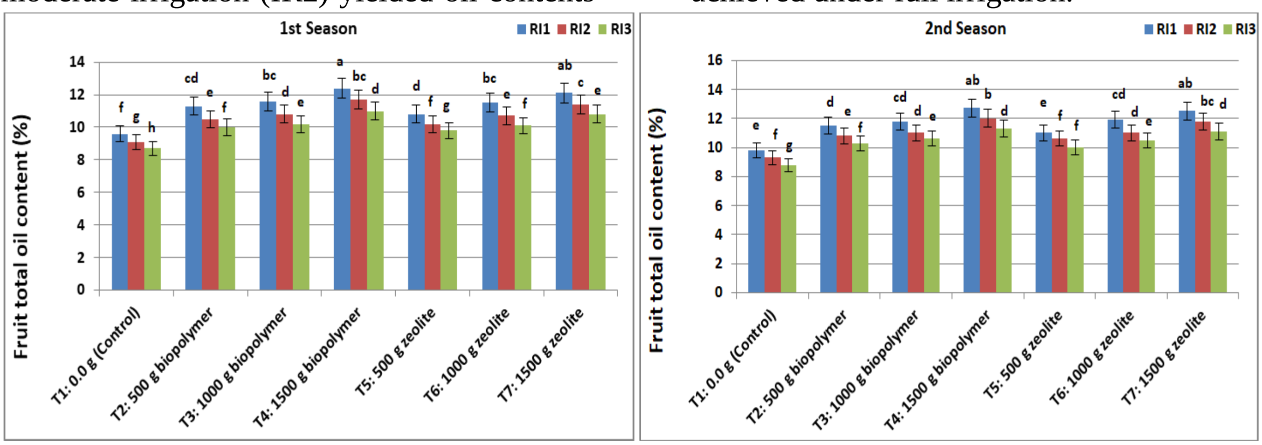

Fig. (9). Influence of deficit irrigation and absorbent material application on fruit total oil content (%) of Hass avocado tree over 2023 and 2024 seasons.

Discussion

The present study demonstrates that both deficit irrigation and the application of soil absorbent materials significantly influenced the vegetative growth and physiological performance of Hass avocado trees over two consecutive seasons. Across all measured parameters, moderate water deficit (IR2, 80% of full irrigation) combined with biopolymer application, particularly at 1000 g (T3), consistently enhanced shoot growth, leaf development, and stomatal conductance compared to the control and zeolite treatments under similar or more severe water deficits. These findings suggest that soil water retentive amendments can partially mitigate the negative effects of reduced irrigation, sustaining tree vigor and productivity under conditions of limited water availability. Shoot length and diameter responded positively to biopolymer treatments, with the greatest values recorded under moderate water deficit in both seasons. This pattern can be attributed to the ability of hydrophilic polymers to retain soil moisture and release it slowly to the root zone, thus supporting continuous cambial activity even under reduced irrigation. Similar trends were observed by Ahmed et al. (2022), who reported that soil conditioners enhanced vegetative growth of avocado under semi-arid conditions. The slight increase in growth parameters during the second season likely reflects cumulative effects of improved root soil interactions and greater efficiency in water utilization following the establishment of the absorbent materials in the soil profile. In contrast, severe water deficit (IR3) markedly suppressed shoot elongation and thickening, consistent with previous findings that avocado is highly sensitive to water stress, which limits cell expansion and primary growth (Carr, 2013). Leaf production and expansion were similarly affected by irrigation and soil amendments. The highest number of leaves per shoot and the largest leaf areas were consistently observed in T3 under IR2, while zeolite and control trees under IR3 showed significant reductions. These results align with the physiological principle that leaf development is highly sensitive to water status; under moderate deficit, stomatal closure and turgor reduction lead to limited cell expansion, smaller lamina size, and leaf abscission (Chartzoulakis et al., 2002). The enhanced performance of biopolymer treated trees indicates that these amendments improve soil water holding capacity, thereby maintaining higher leaf turgor and photosynthetic surface area even under partial deficit conditions. The second season improvement in leaf area and retention can be attributed to better soil moisture distribution and the gradual establishment of a more efficient root system supported by the water storing materials, as previously documented in studies on soil hydrogels and fruit trees under deficit irrigation (Hüttermann et al., 2009). Stomatal conductance (g) provided further insight into the physiological response of avocado trees to the combined treatments. Trees receiving 1000 g biopolymer under IR2 maintained the highest Stomatal conductance values in seasons, reflecting improved gas exchange and likely higher photosynthetic capacity. In contrast, severe water deficit (IR3), particularly in control and zeolite treatments, resulted in pronounced reductions in g, indicating early stomatal closure as a drought avoidance mechanism. This behavior is consistent with avocado's known isohydric response to water stress, where stomatal regulation is one of the first defense strategies to limit transpiration and prevent xylem cavitation (Zuluaga et al., 2021). The observed second-season increase in g suggests that biopolymer application gradually enhanced plant water status and stress tolerance, leading to more efficient stomatal behavior. These findings agree with the reports of Yahyazadeh et al. (2020), who observed that soil amendments improved physiological performance in deficit irrigated fruit trees by enhancing soil moisture buffering. Biopolymer performance, especially at 1500 g per tree, likely stems from its superabsorbent matrix, which can retain several hundred times its weight in water. Similar findings in grapes showed that natural polymer amendment-maintained leaf water potential and (Pn) under drought by releasing stored moisture during critical transpiration periods (Toma et al, 2024). Zeolite's cation exchange capacity also improves water retention and root hydration, as documented in sandy soils where 1000–1500 g m^2 zeolite reduced water stress indicators in citrus under limited irrigation. Seasonal consistency of treatment effects suggests that the benefits of absorbent materials persist across varying climatic conditions, aligning with reports that soil amendments stabilize plant water relations year-round in arid orchards (Dodd and Pérez-Alfocea, 2012). From an agronomic standpoint, integrating 1500 g biopolymer or zeolite per tree under regulated deficit irrigation regimes (IR2–IR3) can optimize water use efficiency and crop resilience in water scarce regions. Yield responded strongly to the interaction between irrigation regime and amendment dose/type across both seasons. Under full irrigation (IR1), high dose amendments (T4, T7) delivered the greatest yields, while under moderate (IR2) and severe (IR3) deficits, both biopolymer and zeolite consistently mitigated yield losses relative to the unamended control. The stability of this pattern across years indicates that improved rootzone water availability and nutrient retention translated into sustained sink activity during critical phenophases, aligning with the known sensitivity of avocado to soil water status (Carr, 2013 and Padilla-Díaz et al., 2016). The superiority of higher doses reflects a clear dose response, especially under IR2, where water savings did not compromise assimilate supply to developing fruits.

Enhanced fruit set and higher fruit numbers in T4 and T7 under IR1 and their clear advantages over controls under IR2 and IR3 are consistent with the physiological chain observed in the canopy: higher relative water content, improved stomatal conductance, and greater chlorophyll index supported carbon gain and reduced abscission pressure during fruitlets drop. By buffering midday water potential swings, the amendments likely reduced ethylene mediated abscission and maintained ovary retention, an effect reported for water retentive conditioners in fruit trees under partial deficit (Chartzoulakis et al., 2002 and Yahyazadeh et al., 2020). Under IR2, the stepwise improvements from 500 to 1500 g indicate that amendment-driven microenvironmental stability can substitute part of the irrigation buffer usually needed to secure reproductive success. Fruit weight, length, and width followed the same hierarchy as yield: maxima at high doses under IR1, with significant attenuation of size penalties under IR2 and IR3. Given avocado's cell expansion dominated growth during mid-season, improvements in leaf water status (RWC), stomatal conductance, and leaf K and Ca concentrations plausibly promoted turgor-driven expansion and maintained membrane integrity in the mesocarp (Chartzoulakis et al.,2002). The stronger response at higher doses suggests a threshold of soil water storage and release capacity beyond which diurnal shrinks well cycles are sufficiently damped to protect cell enlargement. These findings agree with reports that hydrogels and zeolites enhance fruit size in sandy soils by stabilizing the rhizosphere water film and moderating evaporative demand experienced by roots (Hüttermann et al., 2009 and Sheng and He, 2008). The increase in D/L ratio (more rounded fruit) in high dose treatments under IR1 and IR2 reflects reduced anisotropic growth constraints under water stress. Elongation typically dominates when turgor is limiting, while isotropic expansion improves as water and K/Ca supply stabilize cell wall extensibility. The consistent gains across seasons imply that amendments moderated episodic stress during the rapid expansion window, a quality relevant trait with potential effects on puckout uniformity and consumer preference. Higher fruit carbohydrate and oil contents in amended trees, particularly at 1500 g under IR1 and IR2, point to two reinforcing mechanisms; greater source strength (higher chlorophyll index and stomatal conductance-maintained photosynthesis under partial deficit) and improved phloem loading/transport due to sustained leaf mineral status (notably K and Mg). Because avocado oil accumulation is tightly tied to assimilate supply and metabolic energy later in fruit development, the observed increments under high dose amendments are consistent with improved carbon economy and lipid biosynthesis (Moreno-Ortega et al., 2019). Under IR3, amendments still raised carbohydrates and oil over the control, suggesting that even limited water buffering can preserve enough photosynthate for quality deposition.

CONCLUSION

Deficit irrigation reduced vegetative growth, physiological performance, and yield in 'Hass' avocado; however, the application of soil absorbent materials, especially at higher doses, effectively mitigated these effects. Biopolymer and zeolite at 1500 g/ tree each sustained superior water status, nutrient balance, photosynthetic capacity, and fruit quality under both full and deficit irrigation.

Notably, combining optimal irrigation scheduling with these amendments achieved substantial gains in yield stability, offering a practical strategy for water limited environments. For commercial adoption in Egypt and similar climates, integrating high dose absorbent materials into orchard management could enhance economic returns while contributing to sustainable water resource use. Further multi season and multi-site evaluations are recommended to refine dose response relationships, assess long term soil impacts, and develop cost benefit models tailored to growers' economic contexts.

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الملخص العربي

تأثير نقص المياه وإضافة المواد المحسنة والممتصة للماء على الافوكادو صنف "هاس": أ- النمو الخضري، المحصول وجودة الثمار.

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في دراسة ميدانية عام (2023-2024) تم إجراؤها لتقييم تأثير مادتين ماصتين للمياه (بيبوليمر، زيوليت) بجرعات (500، 1000، و1500جرام /شجرة) تحت ثلاثة أنظمة ري (100٪، 80٪، و70٪من احتياجات الرى) على النمو الخضري، المحصول وجودة الثمار لصنف 'هاس'. وجد ان كلتا الإضافتين زادت بشكل كبير من نمو الأفرع، مساحة الأوراق ومحتوى المياه النسبي مقارنة بأشجار الكنترول، خصوصًا تحت نقص الري المتوسط (80 %). في المعاملات ذات تركيز عالي (1500جرام/شجرة) من البيبوليمر أو الزيوليت زاد المحصول (حتى 30% اعلى من أشجار الكنترول) تحت الري الكامل. نقص الري مع اضافه المواد الماصة للمياه ممكن ان يدعم النمو الخضري، الإنتاجية وجودة الثمار في بساتين الأفوكادو التي تواجه مشكلات نقص المياه.