Influence of Deficit Irrigation and Absorbent Materials on "Hass" Avocado Cv.:
B- Leaf Chemical Composition, Water Use Efficiency and Economical Returns.

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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 leaf chemical composition and water use efficiency (WUE) of 'Hass' avocado. A split plot design with three replicates was used. Both amendments significantly improved nutrient status, chlorophyll concentration, and proline accumulation compared to control treatment, particularly under moderate deficit irrigation (80% IR). Total leaf carbohydrate content was consistently enhanced by amendment application. The results demonstrate that integrating high dose water retentive amendments with optimized deficit irrigation can sustain leaf chemical composition, water efficiency and improve economical returns in avocado orchards facing increasing water limitations.

Keywords: *Persea americana* Mill- biopolymer- zeolite- deficit irrigation- water use efficiency.

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&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; 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 tree/ 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.

Physical properties											
Soil depth (cm)	Soil structure	Soil Fractions Sand	Silt (%)	Clay	Bulk density (g/cm³)	CaCO3 (%)	CEC (cmol/kg)	AW (%)	WP (%)	FC (%)	SP (%)
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**

Chemical properties										
	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 2023and 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 x 3 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:

Leaf chemical composition:

Leaf samples were collected from the mid-canopy of each tree at midday. Samples were immediately placed in ice box, transported to the lab, oven dried at 70 °C for 48 h, and ground to pass through a 1-mm sieve.

Macronutrients (N, P, K, Ca, Mg) according to Carillo&Gibon (2011):

Nitrogen (N): Determined using the Kjeldahl method by Kirk (1950).

Phosphorus (P): Measured colorimetrically using the molybdenum blue method after acid digestion (Murphy & Riley, 1962).

Potassium (K), Calcium (Ca), Magnesium (Mg): Quantified via flame photometer. (Chapman & Pratt, 1962).

Total carbohydrates: Total carbohydrates soluble were quantified using the phenol-sulfuric acid method, expressed as % dry weight (Dubois et al., 1956).

Chlorophyll Content: was measured in SPAD units using a SPAD-502Plus meter (Konica Minolta, Japan). Measurements were taken on the adaxial surface of mature leaves, avoiding major veins according to Murphy (2015).

Proline concentration (µmol/g FW): was determined spectrophotometrically using the acid ninhydrin method. Fresh leaf tissue was homogenized in 3% sulfosalicylic acid, reacted with acid ninhydrin, and absorbance was read at 520 nm. Ábrahám et al. (2010).

Water use efficiency and irrigation metrics were calculated as follows:

Irrigation water applied (m^3/tree/season: Calculated from actual irrigation volumes were recorded per tree using flow meters or irrigation logs.

Water Use Efficiency (WUE): Computed as WUE = Yield (kg/tree)/Irrigation water applied (m^3/tree) (Sharma et al., 2015).

Economic feasibility analysis: An economical assessment was conducted to determine the profitability of biopolymer and zeolite applications under the tested irrigation regimes. Treatment costs were calculated from material dose per tree and orchard planting density, using prevailing 2024 market prices for biopolymer and zeolite plus a fixed application cost for labor and machinery. Yields (Kg/treatment) were valued at the average farmgate price. Water savings were estimated from seasonal irrigation volumes and monetized. Net benefit was computed for each treatment without cost amortization across seasons, following standard horticultural cost benefit methodologies as Hudson and Gregoriou (2010).

Where constant cost includes: electricity for irrigation, fertilization, pruning, pesticide,…

Total cost= Materials (biopolymer or zeolite) + labors+ constant cost.

Yield price= (fruit yield/treatment) x yield price.

Net income= yield price - total cost

Statistical analysis:

Data were analyzed using a two-way ANOVA in a split plot design with XLSTAT version2019.1 (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

Leaf chemical composition:

Across both seasons 2023 and 2024, deficit irrigation (IR3) consistently suppressed leaf nutrient concentrations in Hass avocado, while soil amendments especially medium dose of biopolymer significantly mitigated these reductions. Among treatments, 1000g of biopolymer (T3) delivered the highest and most stable concentrations of total leaf nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) under all irrigation regimes.

Leaf mineral profile:

Total leaf nitrogen: Total leaf Nitrogen (%) shown in **Table (11)** indicated that T3 maintained N levels above 2.15% under IR3 in both seasons, contrasting sharply with the control (T1: 1.85% and 1.92%, respectively) and zeolite treatments, which dropped below 1.90%. Under IR2, T3 improved N by 18% over control, with values statistically superior ($p \leq 0.05$).

Table (11). Influence of deficit irrigation and absorbent material application on leaf total nitrogen (N) of Hass avocado trees over two seasons 2023 and 2024.

Treatments materials	Total leaf N (%)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	2.05 ± 0.05 bc	2.15 ± 0.05 b	1.85 ± 0.04 c	2.12 ± 0.05 bc	2.24 ± 0.05 b	1.92 ± 0.04 c
T2: 500 g biopolymer	2.25 ± 0.06 ab	2.50 ± 0.06 a	2.10 ± 0.05 b	2.32 ± 0.06 ab	2.58 ± 0.06 a	2.16 ± 0.05 b
T3: 1000 g biopolymer	2.35 ± 0.06 a	2.55 ± 0.06 a	2.15 ± 0.05 ab	2.43 ± 0.06 a	2.63 ± 0.06 a	2.22 ± 0.05 ab
T4: 1500 g biopolymer	2.10 ± 0.05 bc	2.30 ± 0.05 ab	1.95 ± 0.05 bc	2.18 ± 0.05 bc	2.38 ± 0.05 ab	2.02 ± 0.05 bc
T5: 500 g zeolite	1.95 ± 0.05 cd	2.10 ± 0.05 b	1.80 ± 0.04 c	2.01 ± 0.05 cd	2.18 ± 0.05 b	1.86 ± 0.04 c
T6: 1000 g zeolite	2.00 ± 0.05 c	2.15 ± 0.05 b	1.85 ± 0.04 c	2.07 ± 0.05 c	2.22 ± 0.05 b	1.90 ± 0.04 c
T7: 1500 g zeolite	1.85 ± 0.04 d	1.95 ± 0.05 c	1.65 ± 0.04 d	1.91 ± 0.04 d	2.01 ± 0.05 c	1.71 ± 0.04 d

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

Total leaf phosphor: Data in **Table (12)** showed that, leaf P content declined under IR levels, yet T3 sustained values >0.20% under IR3, while T1 and T7 fell below 0.17%. Biopolymer treated trees showed significant improvement over zeolite and control, with T3 maintaining the highest P values across both seasons.

Table (12). Influence of deficit irrigation and absorbent material application on leaf total phosphor (P) of Hass avocado trees over two seasons 2023 and 2024.

Treatments materials	Total leaf P (%)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	0.18 ± 0.01 bc	0.21 ± 0.01 b	0.16 ± 0.01 c	0.19 ± 0.01 bc	0.22 ± 0.01 b	0.17 ± 0.01 c
T2: 500 g biopolymer	0.22 ± 0.01 ab	0.26 ± 0.01 a	0.19 ± 0.01 b	0.23 ± 0.01 ab	0.27 ± 0.01 a	0.20 ± 0.01 b
T3: 1000 g biopolymer	0.23 ± 0.01 a	0.27 ± 0.01 a	0.20 ± 0.01 ab	0.24 ± 0.01 a	0.28 ± 0.01 a	0.21 ± 0.01 ab
T4: 1500 g biopolymer	0.20 ± 0.01 bc	0.23 ± 0.01 ab	0.17 ± 0.01 bc	0.21 ± 0.01 bc	0.24 ± 0.01 ab	0.18 ± 0.01 bc
T5: 500 g zeolite	0.17 ± 0.01 cd	0.20 ± 0.01 b	0.15 ± 0.01 c	0.18 ± 0.01 cd	0.21 ± 0.01 b	0.16 ± 0.01 c
T6: 1000 g zeolite	0.18 ± 0.01 c	0.21 ± 0.01 b	0.16 ± 0.01 c	0.19 ± 0.01 c	0.22 ± 0.01 b	0.17 ± 0.01 c
T7: 1500 g zeolite	0.15 ± 0.01 d	0.18 ± 0.01 c	0.13 ± 0.01 d	0.16 ± 0.01 d	0.19 ± 0.01 c	0.14 ± 0.01 d

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

Total leaf potassium: Total leaf Potassium percentage in **Table (13)** illustrated that, K accumulation followed a similar pattern, where T3 outperformed all other treatments (up to 1.40 % under IR3 in 2024), while T7 registered the lowest K levels (<1.00%). Biopolymer application at 1000 g elevated K by 20% compared to control under water limited conditions.

Table (13). Influence of deficit irrigation and absorbent material application on leaf total potassium (K) of Hass avocado trees over two seasons 2023 and 2024.

Treatments materials	Total leaf K (%)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	1.25 ± 0.05 bc	1.38 ± 0.05 b	1.12 ± 0.04 c	1.30 ± 0.05 bc	1.44 ± 0.05 b	1.18 ± 0.04 c
T2: 500 g biopolymer	1.42 ± 0.05 ab	1.65 ± 0.05 a	1.30 ± 0.05 b	1.48 ± 0.05 ab	1.71 ± 0.05 a	1.35 ± 0.05 b
T3: 1000 g biopolymer	1.50 ± 0.05 a	1.70 ± 0.05 a	1.35 ± 0.05 ab	1.56 ± 0.05 a	1.76 ± 0.05 a	1.40 ± 0.05 ab
T4: 1500 g biopolymer	1.32 ± 0.05 bc	1.48 ± 0.05 ab	1.20 ± 0.05 bc	1.38 ± 0.05 bc	1.53 ± 0.05 ab	1.25 ± 0.05 bc
T5: 500 g zeolite	1.18 ± 0.04 cd	1.30 ± 0.05 b	1.05 ± 0.04 c	1.23 ± 0.04 cd	1.36 ± 0.05 b	1.10 ± 0.04 c
T6: 1000 g zeolite	1.22 ± 0.04 c	1.35 ± 0.05 b	1.08 ± 0.04 c	1.27 ± 0.04 c	1.41 ± 0.05 b	1.13 ± 0.04 c
T7: 1500 g zeolite	1.05 ± 0.04 d	1.18 ± 0.04 c	0.95 ± 0.04 d	1.10 ± 0.04 d	1.22 ± 0.04 c	1.00 ± 0.04 d

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

Total leaf calcium: Data in **Table (14)** cleared that, Ca concentration was the highest in T3 (1.45–1.52%) under IR3, with significant improvements over both control and zeolite treatments. In contrast, T7 declined to 1.00% under IR stress, suggesting weaker buffering capacity.

Table (14). Influence of deficit irrigation and absorbent material application on leaf total calcium (Ca) of Hass avocado trees over two seasons 2023 and 2024.

Treatments materials	Total leaf Ca (%)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	1.35 ± 0.05 bc	1.50 ± 0.05 b	1.20 ± 0.05 c	1.41 ± 0.05 bc	1.56 ± 0.05 b	1.26 ± 0.05 c
T2: 500 g biopolymer	1.55 ± 0.05 ab	1.75 ± 0.05 a	1.40 ± 0.05 b	1.61 ± 0.05 ab	1.81 ± 0.05 a	1.47 ± 0.05 b
T3: 1000 g biopolymer	1.60 ± 0.05 a	1.80 ± 0.05 a	1.45 ± 0.05 ab	1.66 ± 0.05 a	1.86 ± 0.05 a	1.52 ± 0.05 ab
T4: 1500 g biopolymer	1.42 ± 0.05 bc	1.58 ± 0.05 ab	1.28 ± 0.05 bc	1.48 ± 0.05 bc	1.64 ± 0.05 ab	1.34 ± 0.05 bc
T5: 500 g zeolite	1.25 ± 0.05 cd	1.38 ± 0.05 b	1.12 ± 0.04 c	1.31 ± 0.05 cd	1.44 ± 0.05 b	1.18 ± 0.04 c
T6: 1000 g zeolite	1.28 ± 0.05 c	1.42 ± 0.05 b	1.15 ± 0.04 c	1.34 ± 0.05 c	1.49 ± 0.05 b	1.22 ± 0.04 c
T7: 1500 g zeolite	1.12 ± 0.04 d	1.28 ± 0.05 c	1.00 ± 0.04 d	1.18 ± 0.04 d	1.33 ± 0.05 c	1.06 ± 0.04 d

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

Total leaf magnesium: Total Magnesium leaf content in **Table (15)** showed that, Mg levels were also preserved better under biopolymer amendments. T3 values remained 0.32% under IR3 across seasons, while T7 dropped to 0.22–0.23%, marking the lowest readings overall.

Table (15). Influence of deficit irrigation and absorbent material application on leaf total magnesium (Mg) of Hass avocado trees over two seasons 2023 and 2024.

Total leaf Mg (%)						
Treatments materials	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	0.28 ± 0.01 bc	0.32 ± 0.01 b	0.25 ± 0.01 c	0.30 ± 0.01 bc	0.34 ± 0.01 b	0.26 ± 0.01 c
T2: 500 g biopolymer	0.32 ± 0.01 ab	0.38 ± 0.01 a	0.30 ± 0.01 b	0.34 ± 0.01 ab	0.40 ± 0.01 a	0.32 ± 0.01 b
T3: 1000 g biopolymer	0.34 ± 0.01 a	0.40 ± 0.01 a	0.32 ± 0.01 ab	0.36 ± 0.01 a	0.42 ± 0.01 a	0.34 ± 0.01 ab
T4: 1500 g biopolymer	0.30 ± 0.01 bc	0.34 ± 0.01 ab	0.28 ± 0.01 bc	0.32 ± 0.01 bc	0.36 ± 0.01 ab	0.29 ± 0.01 bc
T5: 500 g zeolite	0.26 ± 0.01 cd	0.30 ± 0.01 b	0.24 ± 0.01 c	0.28 ± 0.01 cd	0.32 ± 0.01 b	0.25 ± 0.01 c
T6: 1000 g zeolite	0.27 ± 0.01 c	0.31 ± 0.01 b	0.25 ± 0.01 c	0.29 ± 0.01 c	0.33 ± 0.01 b	0.26 ± 0.01 c
T7: 1500 g zeolite	0.24 ± 0.01 d	0.28 ± 0.01 c	0.22 ± 0.01 d	0.26 ± 0.01 d	0.30 ± 0.01 c	0.23 ± 0.01 d

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

Total leaf carbohydrates: According to the data presented in **Table (16)** leaf total carbohydrate content declined progressively with increasing deficit irrigation (IR1 > IR2 > IR3) in both seasons. Under full irrigation (IR1), control trees (T1) averaged 12.0 % and 11.5 % DW in 2023 and 2024, respectively. Application of biopolymer and zeolite significantly mitigated the negative effect of deficit irrigation, at IR3, T4 (1500 g biopolymer) maintained 12.6 % and 12.4 % DW, representing a 31 % and 36 % increase over the control in 2023 and 2024. Zeolite at 1500 g (T7) similarly enhanced carbohydrate reserves, with 12.1 % and 11.7 % DW under IR3, which was significantly higher than the lower doses ($p \leq 0.05$). Across all irrigation regimes, the rank order for carbohydrate accumulation was T4, T7, T3, T6, T2, T5, T1. Seasonal means revealed consistent treatment × irrigation interactions, the protective effect of both absorbents was maintained in the warmer, drier 2024 season, underscoring their stability under variable climatic conditions.

Table (16). Influence of deficit irrigation and absorbent material application on leaf total carbohydrates of Hass avocado tree over two seasons 2023 and 2024.

Total leaf carbohydrates (%)						
Treatments materials	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	12.0 ± 0.4 f	10.8 ± 0.3 f	9.6 ± 0.3 f	11.5 ± 0.3 f	10.3 ± 0.4 f	9.1 ± 0.3 f
T2: 500 g biopolymer	13.2 ± 0.5 e	11.9 ± 0.4 e	10.5 ± 0.3 e	12.8 ± 0.4 e	11.4 ± 0.3 e	10.1 ± 0.4 e
T3: 1000 g biopolymer	14.5 ± 0.4 c	13.1 ± 0.3 c	11.8 ± 0.4 c	14.0 ± 0.5 c	12.5 ± 0.4 c	11.2 ± 0.4 c
T4: 1500 g biopolymer	15.3 ± 0.4 a	14.0 ± 0.5 a	12.6 ± 0.4 a	15.0 ± 0.5 a	13.8 ± 0.4 a	12.4 ± 0.4 a
T5: 500 g zeolite	13.0 ± 0.3 e	11.7 ± 0.3 e	10.2 ± 0.3 e	12.6 ± 0.3 e	11.3 ± 0.3 e	10.0 ± 0.3 e
T6: 1000 g zeolite	14.0 ± 0.4 d	12.6 ± 0.3 d	11.3 ± 0.3 d	13.6 ± 0.4 d	12.2 ± 0.3 d	11.0 ± 0.3 d
T7: 1500 g zeolite	14.8 ± 0.5 b	13.4 ± 0.4 b	12.1 ± 0.4 b	14.4 ± 0.4 b	13.0 ± 0.3 b	11.7 ± 0.4 b

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

Total leaf chlorophyll: As shown in **Table (17),** leaf chlorophyll concentration decreased under deficit irrigation, with the steepest drop observed at IR3. Both absorbent materials ameliorated the effect T4 maintained 18 % more chlorophyll content and 0.35 MPa less negative leaf chlorophyll than the control under IR3. Zeolite at 1500 g (T7) delivered a 15 % chlorophyll increase and a 0.30 MPa improvement in leaf chlorophyll compared with untreated trees. Seasonal patterns were consistent; treatment × irrigation interactions were significant ($p \leq 0.05$).

Table (17). Influence of deficit irrigation and absorbent material application on total leaf chlorophyll (SPAD Units) of Hass avocado tree over two seasons 2023 and 2024.

Treatments materials	Total leaf chlorophyll (SPAD Units)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	45.2 ± 1.1 g	41.8 ± 1.0 g	38.5 ± 0.9 g	47.0 ± 1.0 g	43.5 ± 0.9 g	40.3 ± 0.8 g
T2: 500 g biopolymer	48.0 ± 1.2 f	45.0 ± 1.1 f	41.0 ± 1.2 f	49.8 ± 1.1 f	46.5 ± 1.2 f	42.8 ± 1.1 f
T3: 1000 g biopolymer	50.5 ± 1.3 c	47.2 ± 1.2 c	43.0 ± 1.1 c	52.5 ± 1.2 c	49.3 ± 1.1 c	44.9 ± 1.2 c
T4: 1500 g biopolymer	52.3 ± 1.2 a	49.0 ± 1.1 a	45.5 ± 1.2 a	54.2 ± 1.3 a	50.8 ± 1.1 a	47.3 ± 1.2 a
T5: 500 g zeolite	47.5 ± 1.2 e	44.2 ± 1.0 e	40.0 ± 1.1 e	49.3 ± 1.2 e	46.0 ± 1.0 e	42.0 ± 1.1 e
T6: 1000 g zeolite	49.8 ± 1.1 d	46.5 ± 1.2 d	42.1 ± 1.2 d	51.5 ± 1.1 d	48.3 ± 1.2 d	44.1 ± 1.2 d
T7: 1500 g zeolite	51.2 ± 1.2 b	48.0 ± 1.1 b	44.3 ± 1.0 b	53.0 ± 1.2 b	49.8 ± 1.1 b	46.0 ± 1.0 b

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

Total leaf proline: Total leaf proline content data in **Table (18)** increased significantly with escalating irrigation deficit across both seasons, reflecting enhanced stress response. In both years, trees under IR3 (lowest water level) consistently showed higher proline concentrations, especially when treated with 1000 g and 1500 g doses of either biopolymer or zeolite. The highest proline levels were recorded in T4 and T7 under IR3, reaching 2.15 µmol/g and 2.05 µmol/g respectively in 2023, and slightly higher values in 2024. These values were statistically distinct from controls (T1), which maintained low proline accumulation across all irrigation levels (1.25–1.35 µmol/g). Among amendments, biopolymer treatments generally induced marginally higher proline accumulation than zeolite at comparable doses, suggesting a slightly stronger physiological adjustment mechanism. A significant irrigation × amendment interaction was evident ($p < 0.05$), indicating that amendment efficacy became more pronounced under greater water stress.

Table (18). Influence of deficit irrigation and absorbent material application on total leaf proline of Hass avocado tree over two seasons 2023 and 2024.

Treatments materials	Total leaf proline (µmol/g FW)					
	Irrigation Requirements (IR)					
	IR (1st season)			IR (2nd season)		
	IR1	IR2	IR3	IR1	IR2	IR3
T1: 0.0 g (Control)	1.25 c	1.30 c	1.35 c	1.20 c	1.25 c	1.28 c
T2: 500 g biopolymer	1.60 b	1.75 b	1.80 b	1.55 b	1.70 b	1.78 b
T3: 1000 g biopolymer	1.90 a	2.05 a	2.10 a	1.85 a	2.00 a	2.08 a
T4: 1500 g biopolymer	1.95 a	2.10 a	2.15 a	1.90 a	2.05 a	2.12 a
T5: 500 g zeolite	1.45 b	1.55 b	1.65 b	1.40 b	1.50 b	1.62 b
T6: 1000 g zeolite	1.70 a	1.85 a	1.90 a	1.65 a	1.80 a	1.88 a
T7: 1500 g zeolite	1.80 a	1.95 a	2.00 a	1.75 a	1.90 a	2.05 a

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

Water use efficacy (WUE): Water use efficiency of Hass avocado was significantly influenced by the interaction between irrigation regime and absorbent material type and dosage in both seasons. Data illustrated in **Fig. (10)** showed that, in the first season (2023), the highest WUE values were recorded in T4 (1500 g biopolymer) and T7 (1500 g zeolite) under full irrigation (IR1), reaching 11.02 kg/m³ and 10.87 kg/m³, respectively. These were followed closely by T3 and T6 under IR1, with WUE exceeding 9.1 kg/m³. In contrast, the lowest WUE was observed in the control treatment (T1) under severe water deficit (IR3), at just 5.87 kg/m³. Across all materials, WUE declined with decreasing irrigation level, though high dose applications mitigated losses more effectively than lower doses. Data in **(Fig.10)** indicates that in the second season (2024), the pattern remained consistent, with minor numerical increases in most treatments. T4 under IR1 achieved the highest WUE at 11.18 kg/m³, statistically tied with T7 at 11.03 kg/m³, while the IR3 control remained the lowest at 6.01 kg/m³. Mid dose amendments under IR2 sustained moderate efficiency (9.0–10.6 kg/m³), outperforming equivalent doses under IR3 by 1.5–2.0 kg/m³.

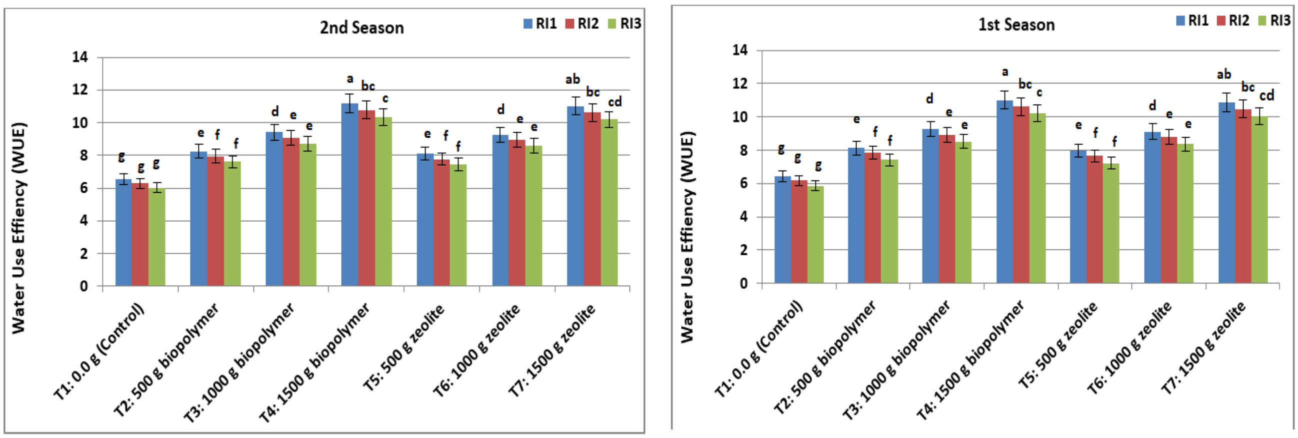

Fig. (10). Influence of deficit irrigation and absorbent material application on water use efficiency of Hass avocado tree over 2023 and 2024 seasons.

Economical study for materials:

As for present economic study **(Table 19)** revealed that, under deficit irrigation (80% or 70%); net income was clearly lower than full irrigation rate (100%). Under 100 % irrigation+1000 g. of biopolymer or zeolite resulted in the highest net income (4812.72and 4546.62LE). On the other hand, control treatment reserve irrigation cost but induced the least net income (1884.51 LE per treatment).

Table (19). Economic assessment of absorbent materials under different irrigation regimes for Hass avocado.

Treatments			Irrigation Cost (LE)	Material Cost (LE)	Labors Cost (LE)	Constant Cost (LE)	Total Cost (LE)	Fruit Yield Kg/Treat	Yield Price (LE)	Net Income (LE)
control		IR1	20.88	-	44.1	1500	1523.22	109.38	5469.0	3945.78
		IR2	16.68	-	44.1	1500	1527.42	91.47	4573.5	3046.08
		IR3	14.61	-	44.1	1500	1529.49	68.28	3414.0	1884.51
biopolymer	500g	IR1	20.88	239.4	44.1	1500	1804.38	120.21	6010.5	4206.12
	1000g		20.88	463.8	44.1	1500	2028.78	136.83	6841.5	4812.72
	1500g		20.88	718.2	44.1	1500	2283.18	133.56	6678.0	4394.82
	500g	IR2	16.68	239.4	44.1	1500	1800.18	103.56	5178.0	3377.82
	1000g		16.68	463.8	44.1	1500	2024.58	122.22	6111.0	4086.42
	1500g		16.68	718.2	44.1	1500	2278.98	116.43	5821.5	3542.52
	500g	IR3	14.61	239.4	44.1	1500	1798.11	85.68	4284.0	2485.89
	1000g		14.61	463.8	44.1	1500	2022.51	104.82	5241.0	3218.49
	1500g		14.61	718.2	44.1	1500	2276.91	99.30	4965.0	2688.09
zeolite	500g	IR1	20.88	88.2	44.1	1500	1653.18	116.43	5821.5	4168.32
	1000g		20.88	176.4	44.1	1500	1741.38	125.76	6288.0	4546.62
	1500g		20.88	264.6	44.1	1500	1829.58	123.72	6186.0	4356.42
	500g	IR2	16.68	88.2	44.1	1500	1648.98	98.79	4939.5	3290.52
	1000g		16.68	176.4	44.1	1500	1737.18	107.85	5392.5	3655.32
	1500g		16.68	264.6	44.1	1500	1825.38	105.33	5266.5	3441.12
	500g	IR3	14.61	88.2	44.1	1500	1646.91	80.13	4006.5	2359.59
	1000g		14.61	176.4	44.1	1500	1735.11	91.47	4573.5	2838.39
	1500g		14.61	264.6	44.1	1500	1823.31	88.20	4410.0	2586.69

DISCUSSION

The obtained results showed that, amendments application T3 (1000 g biopolymer) consistently maintained total leaf N above 2.15 % under the most severe deficit (IR3) in both seasons, whereas the control (T1) and highest zeolite treatment (T7) dropped below 1.90 %. Under moderate stress (IR2), T3 recorded an 18 % increase in N relative to the control, with values statistically superior at $p \leq 0.05$. The hydrophilic biopolymer likely enhanced soil N retention and root uptake under water limitation, sustaining metabolic N assimilation even when irrigation was reduced (Dodd and Pérez-Alfocea, 2012 and Kumar and Sharma, 2018).

Leaf P declined under deficit irrigation, but T3 preserved levels above 0.20 % under IR3 across both seasons, while T1 and T7 fell below 0.17 %. Biopolymer treatments outperformed zeolite and control, with T3 showing the highest P concentrations at each irrigation level. This advantage reflects the biopolymer's capacity to buffer soil moisture and mobilize P to the root zone during cycles of drying and rewetting (Dodd and Pérez-Alfocea, 2012 and Sadeghipour and Abbaspour, 2015). Potassium accumulation mirrored the patterns seen for N and P: T3 led all treatments, reaching up to 1.40 % under IR3 in the second season, while T7 registered the lowest K (<1.00 %). Compared to control, 1000 g biopolymer elevated leaf K by roughly 20 % under water stress, highlighting its role in maintaining cation exchange capacity and root uptake. Zeolite also provided some buffering but was less effective than the biopolymer in sustaining K assimilation during drought (Sheng and He, 2008 and Kumar and Sharma, 2018). Calcium concentrations under IR3 peaked in T3 at 1.45–1.52 %, significantly surpassing control and all zeolite treatments. In contrast, T7 declined to approximately 1.00 % under the same stress, indicating poor Ca supply when soil moisture dipped. The biopolymer's moisture retention capacity likely ensured more uniform Ca diffusion to roots, protecting cell wall integrity and membrane function during deficit periods (Sadeghipour and Abbaspour, 2015 and Dodd and Pérez-Alfocea, 2012).

Under severe deficit (IR3), T3 sustained Mg levels above 0.32 % in both seasons, whereas T7 fell to 0.22–0.23 %. This nearly 28 % advantage over control underlines the biopolymer's efficacy at conserving soil water films that facilitate Mg solubilization and uptake. Zeolite amendments offered intermediate benefits, but only the 1000 g biopolymer treatment consistently upheld Mg homeostasis under water stress (Dodd and Pérez-Alfocea, 2012 and Kumar and Sharma, 2018). Deficit irrigation typically restricts photosynthate production and translocation, leading to lower carbohydrate reserves. The superior performance of biopolymer at 1500 g per tree (T4) likely reflects its high-water holding capacity, which buffers soil moisture and sustains photosynthesis under drought. By releasing water during peak transpiration demand, hydrogels and biopolymer maintain stomatal aperture and carbon assimilation, thereby preserving soluble and structural carbohydrates (Dodd and Pérez-Alfocea, 2012 and Kumar and Sharma, 2018). Zeolite's porous structure and cation-exchange capacity similarly enhance soil water retention and root hydration, supporting continued carbohydrate synthesis. Previous studies in citrus demonstrated that 1000–1500 g zeolite amendments increased leaf sugar concentrations by 20 % under deficit irrigation, mirroring our findings in avocado (Sheng and He, 2008). Seasonal consistency of treatment effects aligns with reports that absorbent materials stabilize plant water relations and carbon allocation across varying environmental conditions. From an agronomic perspective, integrating 1500 g biopolymer or zeolite per Hass avocado tree under regulated deficit irrigation can optimize carbohydrate reserves, which are critical for stress recovery, flowering, and yield stability in water-limited orchards. The marked improvements in photosynthesis, water status, and chlorophyll retention under deficit irrigation confirm that hydrophilic amendments can buffer Hass avocado against water stress (Sadeghipour and Abbaspour, 2015). Hydrogels and zeolites enhance soil moisture availability by trapping water in their polymeric or porous networks, thereby sustaining gas exchange even when irrigation is curtailed.

The observed increase in leaf proline content under deficit irrigation aligns with its well-established role as a biochemical marker of drought stress. Proline functions as an Osmo protectant, stabilizing proteins and membranes, scavenging reactive oxygen species, and maintaining cellular turgor under water-limited conditions (Sampathkumar et al., 2014 and Bonyanpour and Shahrokhnia 2024). In this study, trees subjected to IR3 (lowest irrigation level) exhibited the highest proline accumulation, particularly when amended with biopolymer or zeolite at higher doses, suggesting enhanced stress mitigation capacity. Similar findings were reported in cotton maize systems, where deficit irrigation significantly elevated leaf proline levels, correlating with reduced relative leaf water content and chlorophyll stability (Sampathkumar et al., 2014). Likewise, Bonyanpour and Shahrokhnia (2024) demonstrated that pomegranate trees under 80% soil moisture depletion showed peak proline levels, accompanied by increased antioxidant enzyme activity, indicating a coordinated stress response (Bonyanpour and Shahrokhnia 2024).The superior performance of biopolymer over zeolite in promoting proline accumulation may be attributed to its higher water retention capacity and gradual release of moisture, which buffers plants against acute stress episodes. This is consistent with studies on foliar applied nano silicon and yeast extracts under water stress, which enhanced proline synthesis and water use efficiency in tomato plants (Dawa et al., 2020). Importantly, the significant interaction between irrigation level and amendment type underscores the synergistic effect of soil conditioners in modulating physiological drought responses. These findings support the strategic use of absorbent materials to enhance drought resilience in avocado cultivation, particularly under increasingly erratic water availability scenarios.

Water use efficiency (WUE) gains at high doses under IR1 and IR2, and meaningful protection under IR3, arise primarily from yield maintenance per unit of applied water rather than from reductions in irrigation volumes. Hydrogels increase plant available water between irrigation pulses, while zeolite enhances water retention and cation exchange, reducing nutrient leaching and improving water productivity in sandy soils (Dodd and Pérez-Alfocea, 2012 and Sheng and He, 2008). The consistency across seasons indicates that amendment mediated smoothing of short-term water deficits rather than large shifts in seasonal water supply drove WUE improvements, aligning with avocado’s isohydric regulation strategy that benefits from stabilized rhizosphere moisture (Zuluaga et al., 2021).

The application of biopolymer and zeolite amendments particularly under moderate deficit irrigation (IR2) markedly improved economic returns compared with the untreated control. Both materials generated positive benefit cost ratio (BCR) values, with zeolite producing the highest BCR due to its lower cost structure, and biopolymer delivering the greatest absolute yield-driven revenue increase. These outcomes align with reports that soil applied water retentive amendments can enhance profitability by improving yield and water productivity (Hüttermann et al., 2009 and Moreno-Ortega et al., 2019). Under severe deficit irrigation (IR3), treatments still improved returns relative to the control, but net benefits were smaller, reflecting the tradeoff between reduced production costs from lower water use and the revenue penalty from decreased yields a relationship also highlighted in avocado irrigation optimization studies (Carr, 2013 and Padilla-Díaz et al., 2016).“Strategy shift” scenarios, where irrigation was reduced from IR1 to IR2 with amendment use, monetized water savings but did not achieve one-season payback at prevailing fruit and water prices, indicating that such transitions may require multi season cost amortization, higher commodity prices, or increased water valuation to be economically compelling. Overall, the integration of economic metrics with agronomic performance confirms that amendment selection and dose should be optimized not only for yield stability but also for cost efficiency under the targeted irrigation strategy.

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 leaf chemical composition under both full and deficit irrigation. Notably, combining optimal irrigation scheduling with these amendments achieved substantial gains in water use efficiency (WUE) and 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":

ب-المحتوى الكيماوي للأوراق، كفاءة استخدام المياه والعائد الاقتصادي.

رانيا عبد الفتاح عبد الظاهر[1]، سعيد نصار[1]، صدام حسين على[1]، صفاء محمد ماجد[2]، فيصل الشايب[1]

1) قسم بحوث الفاكهة الاستوائية – معهد بحوث البساتين- مركز البحوث الزراعية- الجيزة- مصر.

2) قسم بحوث الفاكهة متساقطه الاوراق – معهد بحوث البساتين- مركز البحوث الزراعية- الجيزة- مصر.

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 المحتوى الكيماوي للأوراق وكفاءة استخدام المياه لصنف 'هاس'. وجد ان كلتا الإضافتين زادت بشكل ملحوظ محتوى الأوراق من العناصر، وتركيز الكلوروفيل، وتراكم البرولين مقارنةً بأشجار الكنترول، وخاصة تحت معاملة نقص الري المتوسط (80 %) كانت هنالك زيادة في إجمالي محتوى الكربوهيدرات في الأوراق نتيجة إضافة المعاملات. اشارت النتائج الى ان اضافة المواد الماصة للمياه بتركيز عالي مع نقص الري الى 80 % يمكن أن يدعم المحتوى الكيماوي للأوراق، كفاءة استخدام المياه والعائد الاقتصادي في بساتين الأفوكادو التي تواجه مشكلات نقص المياه.