Synergistic Effects of Magnesium Sulfate and Compost on Improving the Productivity of Date Palm Under Drought Stress

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Drought is one of the most significant environmental stress factors negatively affecting fruit tree cultivation because they are highly water-dependent. Water shortage adversely affects the growth and development of fruit trees, leading to a severe reduction in productivity and fruit quality. In particular, drought harms photosynthesis, which is essential to produce carbohydrates. Therefore, developing mitigation strategies and effective water management is vital for maintaining fruit tree health and sustainability. This study was conducted to investigate the influence of adding soil compost individually and in combination with spraying of magnesium sulphate ($MgSO_4$) on improving the soil fertility, productivity, and fruit quality of date palm cv. Barhi. The date trees were fertilized with 5 and 10 kg of compost, and then they were sprayed with 0.5, 0.75, and 1 % $MgSO_4$ four times: starting from mid-February with one-month intervals between sprays, as compared to untreated trees as a control. The results revealed that combining soil-applied compost with foliar spraying of $MgSO_4$ enhanced the productivity and fruit quality of date palm. The best results were obtained by adding 10 kg compost + 1% $MgSO_4$, followed by 10 kg compost + 0.75% $MgSO_4$ and 5 kg compost + 1% $MgSO_4$.

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INTRODUCTION

Dates are rich in essential components, including sugars, proteins, nutrients, fiber, antioxidants, and vitamins (Kamal-Eldin and Ghnimi 2018). Drought represents a critical abiotic stress that limits agricultural productivity across the world, impairing the growth, vitality, yield, and fruit quality of trees due to their substantial dependence on water availability (Šircelj *et al*. 2007; Almutairi *et al*. 2024). Water deficiency leads to a reduction in the photosynthesis process, which is a vital process for producing carbohydrates by converting sunlight into energy, ultimately minimizing the growth and fruit productivity

(Wang *et al*. 2018; Roussos 2020). Various agricultural management practices can be employed to mitigate drought stress, including enhancing soil water retention capacity, increasing organic matter content, and improving soil fertility (Kılıç *et al*. 2024).

Organic fertilizers, particularly compost, are essential components of sustainable agriculture because they improve soil quality by promoting better soil structure and moisture retention, while increasing cation exchange capacity and the availability of essential nutrients. These effects are especially beneficial in sandy soils characterized by low organic matter content and poor nutrient retention. Moreover, the high organic matter content of compost stimulates microbial activity, increasing nutrient and mineral availability for plants and thereby enhancing crop growth and productivity (Diacono and Montemurro 2010; Wang *et al*. 2014). Soil organic matter also plays a vital role in soil fertility by improving the soil's physical, chemical, and biological characteristics, which contribute to higher crop yields and better water infiltration and retention, ultimately increasing plant tolerance to drought conditions (Gokcen and Kuzucu 2023; Kuzucu and Gökçen 2024).

Compost is also effective in optimizing the structural, chemical, and biological traits of soils (Lakhdar *et al*. 2009), and raising the pH of acidic soils (Ch'Ng *et al*. 2014). Roghanian *et al*. (2012) demonstrated that compost amendment stimulates root system development and enhances nutrient acquisition, thereby promoting greater vegetative growth, as reflected in increased stem elongation and plant dry biomass. Furthermore, compost decomposition facilitates nutrient mineralization and improves nutrient solubility, resulting in enhanced soil availability of phosphorus and potassium. Incorporating compost into cultivation soil can enhance crop productivity and increase soil organic matter content (Luo *et al*. 2017). The application of compost is generally recognized to improve soil water retention and increase moisture availability, although its impact can vary widely depending on factors such as soil texture, compost properties, and environmental conditions (Sax *et al*. 2017). Compost use can also influence the soil microbiome, promoting greater microbial diversity (Thompson *et al*. 2019). Compost application contributes to the improvement of soil physicochemical quality by increasing water retention, enhancing cation exchange capacity, improving nutrient bioavailability, and promoting greater soil structural integrity and stability (Hasini *et al.* 2020; Manirakiza and Şeker, 2020). These improvements promote better nutrient uptake and transport within plants by improving the physical, chemical, and biological characteristics of the soil (Gondek *et al*. 2020). In saline soils, compost mitigates the adverse effects of salinity through enhanced nutrient availability and water absorption (Castiglione *et al*. 2021). Consequently, compost application contributes to improved plant nutritional status and overall growth performance (Ud Din *et al*. 2023). Compost serves as a gradual nutrient supplier, fostering enhanced plant growth and agricultural productivity while limiting nitrate leaching into groundwater systems. Consequently, its use can alleviate one of the major environmental challenges associated with intensive synthetic fertilizer application (Jatav *et al.* 2025).

Magnesium (Mg) is a vital macronutrient that performs indispensable functions in plant growth and development. As the central atom of the chlorophyll molecule, it is fundamental to photosynthetic activity. Moreover, Mg serves as a cofactor for numerous enzymatic reactions, facilitates carbohydrate metabolism and transport, supports cellular homeostasis, and plays a critical role in protein biosynthesis and cell division (Verbruggen and Hermans 2013). Mg also enhances plant tolerance to biotic and abiotic stresses, particularly drought and salinity, which can explain why it has become increasingly important in modern agricultural production (Boaretto *et al*. 2020). Furthermore, Mg transporters contribute to proper pollen development, male fertility, and fruit quality (Tian *et al*. 2021; Xu *et al*. 2021). Adequate Mg nutrition enhances fruit quality traits, including flavor, soluble solids, sugar content, and vitamin C concentration, as reported in grapefruit and other citrus crops (Papadakis *et al*. 2023). On the other hand, the deficiency of Mg disrupts nutrient uptake and utilization, reduces photosynthesis, protein synthesis, and carbohydrate transport, and impairs various metabolic processes, leading to reduced plant growth, biomass accumulation, yield, and fruit quality (Ling LiLi *et al*. 2009). In citrus species, Mg deficiency alters nutrient distribution, decreases CO_2 assimilation, impairs cell metabolism and carbohydrate partitioning, and can reduce iron accumulation in roots, ultimately lowering fruit yield and quality (Huang *et al*. 2019; Jia *et al*. 2021). Similar adverse effects have been reported in date palm and grapevine, where Mg deficiency negatively affects plant productivity and fruit quality (Anli *et al*. 2023; Copp *et al*. 2025).

Sulfur (S) is a macronutrient required for plant growth and development (Marschner 2012; Kopriva *et al.* 2019) and is also known to enhance crop quality (Kopriva *et al.* 2015) as well as improve plant responses to abiotic stresses (Santisree *et al.* 2019). A sufficient supply of S throughout all stages of plant growth is essential for optimal crop performance (Edis and Norton 2012). The physiological importance of S is attributed to its role as a fundamental constituent of S-containing amino acids, including methionine, cysteine, and cystine, as well as sulpholipids and various coenzymatic compounds that are essential for cellular metabolism and plant development. Through these functions, S contributes to protein biosynthesis, chlorophyll and B-group vitamin formation, carbohydrate metabolism, and the regulation of plant growth and metabolic activities *via* its interaction with proteolytic enzyme systems (Njira and Nabwami 2015). S deficiency reduces root hydraulic conductivity, a response that may be involved in root-to-shoot signaling of nutrient deprivation (Mitchell 2021).

Therefore, this study was designed to examine the combined effects of soil-applied compost and foliar spraying with magnesium sulfate on the growth and productivity of Barhi date palm, thereby enhancing yield and the fruit's physical and chemical properties.

EXPERIMENTAL

The study was conducted during the 2024 and 2025 seasons on 12-year-old Barhi date palm trees, which were originally planted in the Wadi El-Natroun region of El-Behera Governorate, Egypt. The trees were cultivated in sandy soil, spaced 7 × 7 m^2 apart, and irrigated using a drip irrigation system. Sixty date palm trees, as similar as possible in their vigor, were chosen for this study, where 5 trees (5 replicates) were selected for each treatment. The treatments were organized using a Split Plot Design, with soil compost application serving as the main factor and foliar spraying of $MgSO_4$ as the submain factor, compared to unsprayed trees used as the control. The trees were fertilized with 5 and 10 kg of compost at the start of February 2024. Subsequently, the date palms were sprayed with 0.5, 0.750, and 1 % $MgSO_4$, four times, starting from mid-February with one-month intervals between sprays, compared to untreated trees as a control. The analysis of the experimental soil is shown in Table 1.

Table 1. Physiochemical Soil Characteristics

Textural class			O.M %		pH		CaCO3%				EC (dS/m)	
Sandy loam			0.2		8.3		8.1				4.54	
Soluble anions meq/L)			Soluble cations (meq/L)				Available nutrients (mg/kg)					
							Macro nutrients			Micronutrients		
HCO_3^-	CL^-	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+	N	P	K	Fe	Zn	Mn
8.2	14.8	21.4	14.9	5.6	17.7	6.6	58.00	4.82	271	0.6	0.3	0.71

Table 2. Physiochemical Soil Characteristics After the Addition of Compost

Textural class			O.M %		pH		CaCO3%				EC (dS/m)	
Sandy loam			0.97		7.9		8				3.9	
Soluble anions meq/L)			Soluble cations (meq/L)				Available nutrients (mg/kg)					
							Macro nutrients			Micronutrients		
HCO_3^-	CL^-	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+	N	P	K	Fe	Zn	Mn
7.9	11.4	20.2	13.6	6.1	12.2	7.9	95	10.1	325	0.8	0.4	0.79

Table 3. Meteorological Data of the Experimental Area During the Two Study Seasons

Months	2024				2025			
	Min Air Temp (°C)	Max Air Temp (°C)	Avg RH (%)	Precip. (mm)	Min Air Temp (°C)	Max Air Temp (°C)	Avg RH (%)	Precip. (mm)
January	9.34	20.69	62.53	19.90	9.59	22.25	68.05	1.00
February	8.75	21.54	67.73	7.40	8.25	20.51	60.00	2.60
March	10.76	25.73	58.30	6.80	11.40	27.83	54.08	7.70
April	14.74	31.91	53.62	2.40	13.84	29.88	49.74	1.80
May	17.53	34.33	44.64	0.00	17.47	34.56	42.93	9.10
June	21.65	41.06	45.06	0.10	19.34	37.37	50.54	10.10
July	23.81	40.45	47.57	0.00	22.23	40.02	48.30	1.90
August	23.29	39.96	49.60	0.60	23.51	39.39	49.09	0.00
September	22.56	37.23	51.84	0.00	21.02	36.06	55.55	8.60
Average and Sum	16.94	32.55	53.43	37.20	16.29	31.99	53.14	42.80

Min Air Temp (°C) = Minimum Air Temperature [°C] ; Max Air Temp (°C) = Maximum Air Temperature [°C] ; Avg RH (%) = Average Relative Humidity (%); Precip. (mm) = Total Precipitation (mm)

The effect of the treatments mentioned above was examined by studying their effects on the following parameters.

Palm Yield

At harvest, palm yield was measured in kg, and the total yield per hectare was calculated by multiplying the number of palms by their average yield.

Fruit Quality

In September of 2024 and 2025, at the time of fruit ripening, 40 fruits from each tree (replicate) were harvested and immediately transported to the laboratory for analysis of their physical and chemical characteristics.

Fruit Physical Characteristics

The average fruit weight (g) was obtained by calculating the mean weight of 40 individual fruits. Flesh weight (g) and seed weight (g) were measured, and the flesh-to-fruit ratio was determined. Fruit length and width (cm) were measured using a digital vernier caliper, while fruit firmness (lb/in^2) was evaluated with a Magness–Taylor pressure tester (model FT 02, range 0 to 2 lb, Alfonsine, Italy).

Fruit Chemical Characteristics

The total soluble solids percentage in fresh fruits was measured using a hand-held refractometer. Fruit acidity, expressed as a percentage of malic acid, was determined by titrating fruit juice with 0.1 N sodium hydroxide, using phenolphthalein as an indicator (AOAC 2005). Total sugar content (%) was quantified using the phenol–sulfuric acid method, while reducing sugars were measured colorimetrically following Nelson's procedure (Nielsen 2010). Non-reducing sugar content was calculated by subtracting reducing sugars from total sugars. Ascorbic acid (vitamin C) concentration in the juice was determined *via* titration with 2,6-dichloro phenol-indophenol (Nielsen 2017). Total chlorophyll content was estimated according to Richardson *et al*. (2002), with absorbance measured at 650 nm using a spectrophotometer (Jiangxi Dongling Technology Company, Qingshanhu District, Nanchang City, Jiangxi Province, China). Similarly, carotene content was determined following the method of Aquino *et al*. (2018), with absorbance recorded at 440 nm.

Statistical Analysis

The statistical analysis was performed using a split-plot design in CoHort Software version 6.311 (Pacific Grove, CA, USA). Treatment means were compared using the least significant difference ($LSD_{0.05}$) test as described by Snedecor and Cochran (1990).

RESULTS

Table 4 shows that adding compost to the soil enhanced bunch weight, palm tree yield, and yield per hectare. The improvement became more pronounced when combined with foliar spraying of $MgSO_4$ compared to the control. The highest performance was achieved with the combined treatment of 10 kg compost and 1% $MgSO_4$, surpassing all other treatments. Furthermore, higher foliar doses of $MgSO_4$ were particularly effective in boosting bunch weight and overall productivity of date palm trees in both seasons.

The data in Table 5 demonstrate that when date palm trees were fertilized with compost combined with the spraying of $MgSO_4$, they significantly improved the fruit weight, flesh weight, and flesh fruit ratio compared to untreated trees. Moreover, the soil addition of 10 kg from compost mixed with the spraying of 1% $MgSO_4$, followed by 0.75% $MgSO_4$, notably improved these physical fruit characteristics over the addition of the compost or spraying $MgSO_4$ individually. Additionally, adding 5 kg of compost to the soil and then spraying the date trees with 1% $MgSO_4$ also improved the fruit and flesh weights and flesh-fruit ratio.

Table 4. Effect of the Soil Addition of Compost and the Spraying of Magnesium Sulphate on Date Palm cv. Barhi During 2024 and 2025 Seasons

Soil Application	Foliar Spray	Bunch Weight (kg)		Yield (kg/palm)		Yield (Ton/ha)	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	16.14f	16.34g	129.12f	130.72g	29.44f	29.80g
	0.5% $MgSO_4$	16.42f	16.72fg	131.36f	133.76fg	29.95f	30.50fg
	0.75% $MgSO_4$	16.24f	16.96fg	129.92f	135.68fg	29.62f	30.93fg
	1% $MgSO_4$	17.20ef	17.26fg	137.6ef	138.08fg	31.37ef	31.48fg
5 kg Compost	0% $MgSO_4$	16.4f	16.92fg	131.2f	135.36fg	29.91f	30.86fg
	0.5% $MgSO_4$	17.60e	17.72f	140.8e	141.76f	32.10e	32.32f
	0.75% $MgSO_4$	18.48d	18.58e	147.84d	148.64e	33.71d	33.89e
	1% $MgSO_4$	20.1c	20.64c	160.8c	165.12c	36.66c	37.65c
10 Kg Compost	0% $MgSO_4$	16.58f	17.1fg	132.64f	136.80fg	30.24f	31.19fg
	0.5% $MgSO_4$	20.1c	19.76d	160.8c	158.08d	36.66c	36.04d
	0.75% $MgSO_4$	21.34b	21.54b	170.72b	172.32b	38.92b	39.29b
	1% $MgSO_4$	22.30a	22.4a	178.40a	179.84a	40.67a	41.00a
$LSD_{0.05}$		0.74	0.81	5.96	6.50	1.36	1.48

Table 5. Effect of the Soil Addition of Compost and the Spraying of Magnesium Sulphate on Date Palm cv. Barhi During 2024 and 2025 Seasons

Soil Application	Foliar Spray	Fruit Weight (g)		Flesh Weight (g)		Flesh/Fruit Ratio	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	15.74c	16.14d	14.47d	14.86d	91.95bc	92.07b
	0.5% $MgSO_4$	15.99c	16.58cd	14.68d	15.26cd	91.82c	92.03b
	0.75% $MgSO_4$	16.38c	16.56cd	15.07d	15.24cd	91.98bc	92.00b
	1% $MgSO_4$	18.48b	18.00bc	17.13b	16.63bc	92.65abc	92.38b
5 kg Compost	0% $MgSO_4$	16.45c	16.77cd	15.13d	15.44cd	91.99bc	92.06b
	0.5% $MgSO_4$	17.98b	18.62b	16.62bc	17.25b	92.42abc	92.61b
	0.75% $MgSO_4$	18.43b	19.10b	17.03b	17.72b	92.40abc	92.77ab
	1% $MgSO_4$	20.92a	20.99a	19.50a	19.61a	93.20a	93.41a
10 Kg Compost	0 % $MgSO_4$	17.00c	16.75cd	15.68cd	15.42cd	92.23abc	92.05b
	0.5% $MgSO_4$	20.63a	19.39b	19.21a	18.01b	93.10ab	92.85ab
	0.75% $MgSO_4$	20.78a	21.27a	19.32a	19.88a	92.98abc	93.46a
	1% $MgSO_4$	21.77a	21.43a	20.29a	20.02a	93.17a	93.41a
$LSD_{0.05}$		0.97	1.18	0.95	1.18	0.72	0.55

The addition of 6 or 10 kg from compost, combined with spraying the date trees with $MgSO_4$ improved the fruit length and fruit diameter compared to untreated trees (Table 6). The fruit diameter and fruit firmness significantly improved by the addition of 10 kg compost combined with the spraying of 1% $MgSO_4$ compared to the other applied treatments. The differences between the effects of 10 kg compost combined with the foliar spraying of 1 or 0.75% $MgSO_4$ and 5 kg compost + 1% $MgSO_4$ were insignificant. Moreover, fruit length, diameter, and firmness were improved with the spraying of 1% $MgSO_4$ more than 0.75 or 0.5% $MgSO_4$ in the two seasons.

Table 6. Effect of the Soil Addition of Compost and the Spraying of Magnesium Sulphate on Date Palm cv. Barhi Fruit Quality During 2024 and 2025 Seasons

Soil application	Foliar Spray	Fruit Length (cm)		Fruit Diameter (cm)		Fruit Firmness (lb/inch^2)	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	3.28g	3.31e	2.41e	2.45e	14.22e	14.54e
	0.5% $MgSO_4$	3.32fg	3.35e	2.45e	2.49de	14.52de	14.90e
	0.75% $MgSO_4$	3.43ef	3.43de	2.51de	2.54cde	15.60cd	15.38de
	1% $MgSO_4$	3.49de	3.54cd	2.54de	2.62cd	15.94c	15.98cd
5 kg Compost	0% $MgSO_4$	3.35fg	3.42de	2.48de	2.52cde	14.50de	15.22de
	0.5% $MgSO_4$	3.57cd	3.59bc	2.54de	2.59cde	15.96c	16.20cd
	0.75% $MgSO_4$	3.62bc	3.70ab	2.61cd	2.63c	16.36c	16.68c
	1% $MgSO_4$	3.68abc	3.77a	2.73b	2.76 b	18.10b	18.00b
10 Kg Compost	0% $MgSO_4$	3.44ef	3.46de	2.51de	2.56cde	15.78c	15.88cd
	0.5% $MgSO_4$	3.63bc	3.71ab	2.68bc	2.74b	16.80c	16.74c
	0.75% $MgSO_4$	3.73ab	3.77a	2.77b	2.81b	18.22b	18.42b
	1% $MgSO_4$	3.79a	3.81a	2.89a	2.93a	20.12a	20.70a
$LSD_{0.05}$		0.09	0.11	0.09	0.09	0.94	0.71

Across the two seasons, trees treated with compost in combination with $MgSO_4$ spraying exhibited considerably higher levels of carotene, vitamin C, and chlorophyll in fruits than untreated trees (Table 7). Additionally, the fruit content of carotene and vitamin C was clearly increased by the addition of 10 kg of compost combined with 1% $MgSO_4$ relative to the applied treatments. For chlorophyll content, the highest significant values were obtained by the combined application of 10 kg compost mixed with the spraying of 1% and then with 0.75% $MgSO_4$. The high-sprayed doses from $MgSO_4$ were more efficient in their influence in improving the fruit content from these chemical fruit characteristics rather than the trees that were not sprayed.

Table 7. Effect of the Soil Addition of Compost and the Spraying of Magnesium Sulphate on the Fruit Composition from Carotene, Chlorophyll, and Vitamin C in Date Palm cv. Barhi During 2024 and 2025 Seasons

Soil Application	Foliar Spray	Carotene (mg/100 g)		Total Chlorophyll (mg/100 g)		Vitamin C (mg/100 mL)	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	3.40f	3.57e	5.97f	6.25g	3.20f	3.47c
	0.5% $MgSO_4$	3.59ef	3.6e	6.11 ef	6.30g	3.23ef	3.56c
	0.75% $MgSO_4$	3.87de	4.01e	6.83d	7.13f	3.62cd	3.70c
	1% $MgSO_4$	3.97de	4.47d	7.37c	7.43e	3.64cd	3.70c
5 kg Compost	0% $MgSO_4$	3.60ef	3.86e	6.47de	6.36g	3.29ef	3.66c
	0.5% $MgSO_4$	4.22d	4.47d	7.52 c	7.84d	3.82cd	3.84c
	0.75% $MgSO_4$	4.73c	4.60d	7.80bc	8.33c	3.91c	3.78c
	1% $MgSO_4$	5.07bc	5.14bc	8.20b	8.92b	4.27b	4.11b
10 Kg Compost	0% $MgSO_4$	3.83de	3.88e	6.55de	7.03f	3.53de	3.65c
	0.5% $MgSO_4$	4.83bc	4.97c	7.70bc	8.70b	3.97c	3.79c
	0.75% $MgSO_4$	5.17b	5.37b	8.60a	9.35a	4.27b	4.30b
	1% $MgSO_4$	5.60a	5.72a	8.97a	9.37a	4.71a	4.92a
$LSD_{0.05}$		0.30	0.33	0.38	0.26	0.25	0.22

The fruit content from total soluble solids and also TSS/Acidity ratio were significantly increased *via* the addition of 10 kg compost combined with the spraying of 1% $MgSO_4$. Meanwhile, this treatment markedly reduced the fruit content from acidity percentages compared to the control (Table 8). In both seasons, the application of 10 kg compost with either 0.75% or 0.5% $MgSO_4$ sprays, as well as 5 kg compost + 1% $MgSO_4$, significantly improved fruit TSS% and the TSS/Acidity ratio, while simultaneously lowering fruit acidity compared with other treatments.

Table 8. Effect of the Soil Addition of Compost and the Spraying of Magnesium Sulphate on the Fruit Content from TSS%, Acidity%, and TSS/Acidity in Date Palm cv. Barhi During 2024 and 2025 Seasons

Soil Application	Foliar Spray	TSS%		Acidity%		TSS-Acidity Ratio	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	30.67f	31.00f	0.35a	0.34a	87.02f	92.09f
	0.5% $MgSO_4$	30.73 f	31.47f	0.35a	0.33a	88.00f	94.48f
	0.75% $MgSO_4$	31.63ef	33.27de	0.31bc	0.30abc	101.03ef	111.22de
	1% $MgSO_4$	32.53de	33.83cd	0.31bc	0.30abc	106.48e	111.80de
5 kg Compost	0% $MgSO_4$	31.3ef	32.60e	0.33ab	0.32ab	96.08ef	101.04ef
	0.5% $MgSO_4$	32.93cd	33.87cd	0.30bcd	0.30abc	110.14de	112.08de
	0.75% $MgSO_4$	33.57bcd	34.5bc	0.28cd	0.28bc	120.36cd	121.97cd
	1% $MgSO_4$	34.53b	34.70bc	0.27de	0.27c	129.82c	128.63c
10 Kg Compost	0% $MgSO_4$	31.43ef	33.13de	0.32ab	0.32ab	97.400ef	104.95ef
	0.5% $MgSO_4$	34.00bc	34.63bc	0.27de	0.28bc	127.83c	123.84cd
	0.75% $MgSO_4$	34.60b	35.20b	0.24ef	0.24d	143.08b	146.81b
	1% $MgSO_4$	35.77a	36.30a	0.22f	0.21d	162.78a	170.23a
$LSD_{0.05}$		0.93	0.73	0.02	0.03	10.59	10.51

Table 9. Effect of the Compost Soil Addition and Magnesium Sulphate Spraying on Fruit Content from Total, Reduced, and Non-reduced Sugars in Date Palm cv. Barhi During 2024 and 2025 Seasons

Soil Application	Foliar Spray	Total Sugars (%)		Reduced Sugars (%)		Non-reduced Sugars (%)	
		2024	2025	2024	2025	2024	2025
Zero Compost	0% $MgSO_4$	27.05c	27.17e	21.29d	21.15g	5.75a	6.02a
	0.5% $MgSO_4$	27.26c	27.4e	21.32d	21.72g	5.94a	5.68a
	0.75% $MgSO_4$	27.74c	29.80cd	22.19d	23.60de	5.55a	6.20a
	1% $MgSO_4$	27.93c	30.20bcd	22.26d	23.90cde	5.66a	6.3a
5 kg Compost	0% $MgSO_4$	27.69c	28.73d	22.01d	22.75f	5.68a	5.99a
	0.5% $MgSO_4$	29.67b	30.27bcd	23.36c	24.14cde	6.31a	6.13a
	0.75% $MgSO_4$	29.97b	31.07bc	23.86bc	24.30bcd	6.11a	6.77a
	1% $MgSO_4$	30.68b	31.17bc	24.53bc	24.79bc	6.16a	6.37a
10 Kg Compost	0% $MgSO_4$	27.74c	29.47cd	22.09d	23.30ef	5.65a	6.17a
	0.5% $MgSO_4$	30.33b	31.10bc	23.98bc	24.51bcd	6.35a	6.59a
	0.75% $MgSO_4$	31.08b	31.53b	24.92b	25.18b	6.15a	6.36a
	1% $MgSO_4$	32.63a	33.17a	26.16a	26.80a	6.47a	6.37a
$LSD_{0.05}$		1.10	1.08	0.89	0.67	1.10	0.95

The results demonstrated that the application of compost and foliar spraying with $MgSO_4$ significantly increased both total and reducing sugar contents during the 2024 and 2025 seasons (Table 9). A progressive increase in sugar accumulation was observed as compost amounts increased from 0 to 10 kg and $MgSO_4$ concentrations rose from 0 to 1%. The maximum total sugar contents (32.6 and 33.2%) and reducing sugar contents (26.2 and 26.8%) were achieved with the combined treatment of 10 kg compost and 1% $MgSO_4$, whereas untreated plants exhibited the lowest values. Conversely, non-reducing sugars were not significantly influenced by the treatments, as no significant differences were detected among the means. The positive effect of compost and $MgSO_4$ may be associated with enhanced nutrient availability and improved photosynthetic efficiency, which promote carbohydrate biosynthesis and their subsequent accumulation in fruit tree tissues.

DISCUSSION

The results clearly show that adding compost to the soil improved date palm productivity and fruit quality. These results were explained by many authors who reported that the application of compost improves soil physical, chemical, and biological properties by acting as both a nutrient source and a soil conditioner. Besides, compost increases soil organic matter, dissolved organic carbon, humic substances, nutrient retention and availability, cation exchange capacity, and water-holding capacity, thereby enhancing root development and plant productivity (Lehmann *et al*. 2011; Marschner 2011). By stimulating beneficial microbial and rhizospheric communities, compost improves soil health and functionality. Its incorporation enhances soil structure, increases pore space and water movement, lowers bulk density, and improves hydraulic properties and irrigation efficiency. These effects collectively promote more favorable soil moisture conditions and enhance plant resilience to environmental stresses such as water deficit and salinity (Schulz *et al.* 2014). Furthermore, compost contributes to soil carbon sequestration and climate change mitigation, while reducing production costs and the environmental impacts of agricultural practices through lower requirements for synthetic fertilizers, pesticides, and fuel inputs (Scotti *et al*. 2016).

Bernal *et al*. (2017) and Wang *et al.* (2022) investigated the effects of compost application on soil fertility, crop performance, and environmental impacts, reporting that compost improves soil physical structure, increases nutrient accessibility, and reduces greenhouse gas emissions relative to conventional fertilization systems. Compost improves efficiency of nutrient use, helps preserve soil organic carbon, and enhances soil carbon sequestration, underscoring the importance of sustainable soil management practices for maintaining resilient agricultural systems (Pergola *et al.* 2018; Zhao *et al*. 2020). The application of compost as a soil amendment enhances soil fertility, promotes carbon sequestration, and improves the physical, chemical, and biological characteristics of soil (Sultana *et al.* 2021). In this context, composting aligns effectively with the circular economy concept by promoting nutrient recycling and reducing dependence on synthetic fertilizers. Moreover, it supports sustainable agricultural systems and plays a vital role in ensuring long-term food security (Ajaweed *et al.* 2022). Consequently, compost application enhances crop productivity and tolerance to abiotic stresses, reduces soil erosion, nutrient losses, and dependence on synthetic fertilizers and excessive irrigation, while contributing to improved water quality, reduced environmental pollution, and healthier agroecosystems (Ho *et al*. 2022; Mosa *et al*. 2024). In addition, compost supplies essential macro- and micronutrients, including nitrogen, phosphorus, potassium, iron, copper, zinc, and boron, enhancing nutrient uptake, photosynthetic activity, plant growth, and productivity (Otaiku 2022). It helps maintain soil pH within a favorable range for crop production, promotes nutrient cycling through increased microbial activity, and serves as a slow-release nutrient source that improves long-term soil fertility and nitrogen use efficiency while reducing nutrient losses (Aouass and Kenny 2023; Bremaghani 2024). The incorporation of compost into mango orchards was found to positively influence tree growth and productivity, resulting in enhanced vegetative development, greater fruit retention, increased yield, improved physical and biochemical fruit characteristics, and a more favorable leaf mineral composition compared with non-amended controls (Mosa *et al.* 2024).

The beneficial effects of magnesium (Mg) on yield and on the physical and chemical attributes of fruit are largely explained by its fundamental involvement in a wide range of physiological and biochemical processes that underpin plant growth, nutrient efficiency, and tolerance to environmental stresses. Additionally, Mg is an essential macronutrient and a structural component of the chlorophyll molecule, where it contributes to chlorophyll synthesis and stability, enhances photosynthetic efficiency, and promotes the production of assimilates (Cakmak 2013). Mg also regulates potassium transport across cell membranes, stimulates root activity, and improves nutrient absorption, helping to maintain osmotic balance, stomatal conductance, and enzymatic functions (Hermans *et al*. 2013; Assunção *et al*. 2022). Additionally, Mg also activates more than 300 enzymes involved in photosynthesis, respiration, nucleic acid and protein synthesis, ATP formation and utilization, and other metabolic pathways essential for plant development (Farhat *et al*. 2016; Kleczkowski and Igamberdiev 2021). Mg plays a vital role in carbohydrate production, translocation, and fruit quality by enhancing photosynthesis, facilitating assimilation transport from source leaves to sink organs, and promoting sugar accumulation in horticultural crops such as citrus and apple (Li *et al*. 2017; Liu *et al*. 2022). Adequate Mg nutrition improves the uptake and balance of essential nutrients, including nitrogen, phosphorus, potassium, and calcium, thereby enhancing plant growth, yield, and fruit quality (Ye *et al*. 2019). Furthermore, sufficient Mg levels contribute to soil fertility and rhizosphere health by maintaining nutrient equilibrium, improving nutrient availability, supporting optimal rhizosphere pH, and stimulating beneficial microbial populations in the rhizosphere, particularly mycorrhizal fungi and plant growth-promoting rhizobacteria (Wang *et al.* 2020; Hou *et al.* 2021). Such interactions enhance nutrient absorption, boost tolerance to abiotic stress, and support increased crop productivity alongside long-term agricultural sustainability (Yang *et al.* 2021). In apple cv. Red Fuji, Mg application was shown to improve nitrogen utilization, photosynthesis, anthocyanin biosynthesis, fruit size, fruit weight, and overall productivity (Tian *et al*. 2023). Conversely, Mg deficiency impairs assimilate transport, causes carbohydrate accumulation in leaves, reduces photosynthetic performance, and ultimately decreases crop productivity and fruit quality. Mg is readily mobile in soil and easily lost through leaching, particularly in sandy soils and systems with heavy fertilization; therefore, maintaining adequate Mg levels is vital for maximizing plant development, yield, and fruit quality (Senbayram *et al.* 2015).

Sulphur (S) is an essential nutrient that supports plant growth and productivity through its role in the synthesis of proteins, enzymes, vitamins, chlorophyll, and photosynthetic membrane sulfolipids, thereby enhancing photosynthesis, carbohydrate production, and overall plant development (Brosnan and Brosnan 2006; Maathuis 2009).

S supplementation has been shown to promote cellular division and expansion processes, thereby contributing to the development and enlargement of plant organs and enhancing overall crop growth and productivity (Patel *et al.* 2019), and improve nutrient acquisition and utilization efficiency (Zenda *et al*. 2021). Additionally, it also participates in the biosynthesis and signaling of phytohormones, such as ethylene, hydrogen sulfide, and polyamines, which enhance plant defense mechanisms and improve tolerance to biotic and abiotic stresses (Samanta *et al.* 2020; Jahan *et al.* 2021). S is a significant growth-limiting nutrient and influences the uptake of other nutrients such as N, P, K, molybdenum, zinc, iron, selenium, and boron (Astolfi *et al.* 2021). Besides, it is essential for plant growth and productivity due to its critical role in nutrient acquisition and metabolism. It enhances nitrogen uptake and assimilation by facilitating the incorporation of nitrogen into amino acids and proteins, thereby improving nutrient use efficiency and supporting higher crop yields (Dawar *et al.* 2023). Furthermore, S plays a vital role in chlorophyll biosynthesis, facilitating efficient light energy capture for photosynthesis and supporting plant growth. It is also an essential constituent of numerous enzymes and coenzymes involved in key metabolic processes, particularly nitrogen assimilation, which is fundamental for amino acid and protein synthesis. Consequently, adequate S nutrition enhances growth, development, and productivity, thereby increasing fruit weight and yield, whereas S deficiency impairs chlorophyll formation, reduces photosynthetic efficiency, and ultimately limits crop productivity (Narayan *et al.* 2023).

CONCLUSIONS

1. The combined soil application of compost and foliar spraying of $MgSO_4$, either individually or in combination, significantly improved fruit yield and enhanced physical and chemical fruit quality compared with untreated trees under drought stress conditions.
2. The most effective treatment was the application of 10 kg compost combined with 1% $MgSO_4$, followed by 10 kg compost with 0.75% $MgSO_4$, and then 5 kg compost with 1% $MgSO_4$, all of which showed superior yield and quality performance.
3. The observed improvements in yield and fruit quality may be associated with the use of organic amendments and magnesium supplementation, which are commonly reported to support plant productivity under stress conditions.
4. Overall, compost application in combination with $MgSO_4$ foliar spraying appears to be a promising agronomic practice for improving date palm productivity and fruit quality under drought stress; however, further studies are needed to confirm the underlying effects on soil physicochemical properties.

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Data Availability Statement

All the required data are included in the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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APPENDIX
ANOVA Tables

	Weight of bunch in kg 2024					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	0.6333	0.1583	0.5732	0.6901	ns
Main	2	119.4503	59.7252	216.2323	0.0000	***
Main Plot Error	8	2.2097	0.2762	-	-	-
Sub	3	99.3365	33.1122	98.2152	0.0000	***
Sub × Main	6	43.3390	7.2232	21.4249	0.0000	***
Error	36	12.1370	0.3371	—	—	—
Total	59	277.1058	—	—	—	—
Model	23	264.9688	11.5204	34.1710	0.0000	***
	Weight of bunch in kg 2025					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	1.697333333	0.4243333	0.9248093	0.4952	ns
Mian	2	110.9293333	55.464667	120.88195	0.0	***
Main Plot Error	8	3.670666667	0.4588333			
Sub	3	93.90183333	31.300611	78.013154	0.0	***
Sub * Mian	6	35.48666667	5.9144444	14.741069	0.0	***
Error	36	14.444	0.4012222			
Total	59	260.1298333				
Model	23	245.6858333	10.681993	26.623632	0.0	***

	Yield (kg/palm) 2024					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	40.5333	10.1333	0.5732	0.6901	ns
Main	2	7644.8213	3822.4107	216.2323	0.0000	***
Main Plot Error	8	141.4187	17.6773	-	-	
Sub	3	6357.5360	2119.1787	98.2152	0.0000	***
Sub * Main	6	2773.6960	462.2827	21.4249	0.0000	***
Error	36	776.7680	21.5769	-	-	
Total	59	17734.7733	-	-	-	
Model	23	16958.0053	737.3046	34.1710	0.0000	***
	Yield (kg/palm) 2025					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	108.6293	27.1573	0.9248	0.4952	ns
Main	2	7099.4773	3549.7387	120.8820	0.0000	***
Main Plot Error	8	234.9227	29.3653	-	-	
Sub	3	6009.7173	2003.2391	78.0132	0.0000	***
Sub * Main	6	2271.1467	378.5244	14.7411	0.0000	***
Error	36	924.4160	25.6782	-	-	
Total	59	16648.3093	-	-	-	
Model	23	15723.8933	683.6475	26.6236	0.0000	***

	Yield in ton 2024					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	4	2.1070848	0.5267712	0.5732388	0.6901	ns
Mian	2	397.4083922	198.7042	216.23231	0.0000	***
Main Plot Error	8	7.351507968	0.9189385	—	—	—
Sub	3	330.4901514	110.16338	98.21521	0.0000	***
Sub × Mian	6	144.1878129	24.031302	21.424899	0.0000	***
Error	36	40.37950771	1.121653	—	—	—
Total	59	921.924457	—	—	—	—
Model	23	881.5449492	38.328041	34.171033	0.0000	***
	Yield in ton 2025					
Source	df	Type III SS	MS	F	P	Sig.
Main Plots						
Blocks	4	5.646987264	1.4117468	0.9248093	0.4952	ns
Mian	2	369.0592297	184.52961	120.88195	0.0000	***
Main Plot Error	8	12.2122199	1.5265275	—	—	—
Sub	3	312.4091459	104.13638	78.013154	0.0000	***
Sub × Mian	6	118.0632883	19.677215	14.741069	0.0000	***
Error	36	48.05484134	1.3348567	—	—	—
Total	59	865.4457124	—	—	—	—
Model	23	817.390871	35.538734	26.623632	0.0000	***

	TSS% 2024					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	2	0.361667	0.180833	0.644874	0.5718	ns
Mian	2	40.631667	20.315833	72.448737	0.0007	***
Main Plot Error	4	1.121667	0.280417	—	—	—
Sub plots						
Sub	3	47.149722	15.716574	53.209718	0.0000	***
Sub × Mian	6	6.606111	1.101019	3.727586	0.0138	*
Error	18	5.316667	0.295370	—	—	—
Total	35	101.187500	—	—	—	—
Model	17	95.870833	5.639461	19.092845	0.0000	***
	TSS% 2025					
Source	df	Type III SS	MS	F	P-value	Sig.
Main Plots						
Blocks	2	0.3267	0.1633	0.4404	0.6716	ns
Main	2	36.0650	18.0325	48.6270	0.0016	**
Main Plot Error	4	1.4833	0.3708	—	—	—
Sub Plots						
Sub	3	37.7719	12.5906	68.8850	0.0000	***

Sub × Main	6	2.8506	0.4751	2.5993	0.0541	ns
Error	18	3.2900	0.1828	—	—	—
Total	35	81.7875	—	—	—	—
Model	17	78.4975	4.6175	25.2629	0.0000	***

	Acidity % 2024					
Source	df	Type III SS	MS	F	P-value	Sig.
Main Plots						
Blocks	2	0.003750	0.001875	10.714286	0.0247	*
Mian	2	0.027450	0.013725	78.428571	0.0006	***
Main Plot Error	4	0.000700	0.000175	—	—	—
Sub Plots						
Sub	3	0.025719	0.008573	37.791837	0.0000	***
Sub × Mian	6	0.003372	0.000562	2.477551	0.0633	ns
Error	18	0.004083	0.000227	—	—	—
Total	35	0.065075	—	—	—	—
Model	17	0.060992	0.003588	15.815366	0.0000	***
	Acidity % 2025					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	2	0.000155556	0.000077778	0.3415	0.7296	ns
Mian	2	0.018872222	0.0094361	41.4268	0.0021	**
Main Plot Error	4	0.000911111	0.000227778	—	—	—
Sub	3	0.022541667	0.0075139	25.6804	0.0000	***
Sub × Mian	6	0.004216667	0.000702778	2.4019	0.0698	ns
Error	18	0.005266667	0.000292593	—	—	—
Total	35	0.051963889	—	—	—	—
Model	17	0.046697222	0.0027469	9.3881	0.0000	***

	TSS/acidity 2024					
Source of Variation	df	Type III SS	MS	F-value	P-value	Sign.
Main Plots						
Blocks	2	656.818	328.409	9.525	0.0301	*
Mian	2	8277.136	4138.568	120.035	0.0003	***
Main Plot Error	4	137.912	34.478	–	–	–
Subplots						
Sub	3	7800.622	2600.207	68.208	<0.0001	***
Sub × Mian	6	1763.711	293.952	7.711	0.0003	***
Error	18	686.188	38.122	–	–	–
Total	35	19322.387	–	–	–	–
Model	17	18636.198	1096.247	28.757	<0.0001	***
	TSS/acidity 2025					
Source	df	Type III SS	MS	F	P	Sign.

Blocks	2	23.25065332	11.625327	0.5471166	0.6165	ns
Main	2	7059.255306	3529.6277	166.113	0.0001	***
Main Plot Error	4	84.99341296	21.248353	—	—	—
Sub	3	7566.987217	2522.3291	67.162313	0.0000	***
Sub * Main	6	1939.363825	323.2273	8.6066063	0.0002	***
Error	18	676.0029738	37.555721	—	—	—
Total	35	17349.85339	—	—	—	—
Model	17	16673.85041	980.81473	26.116254	0.0000	***

	Fruit Firmness (lb/inch^2) 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	4	1.3573	0.3393	0.8262	0.5440	ns
Mian	2	66.4343	33.2172	80.8778	0.0000	***
Main Plot Error	8	3.2857	0.4107	—	—	—
Sub	3	88.8873	29.6291	55.4017	0.0000	***
Sub * Mian	6	12.1297	2.0216	3.7801	0.0051	**
Error	36	19.2530	0.5348	—	—	—
Total	59	191.3473	—	—	—	—
Model	23	172.0943	7.4824	13.9908	0.0000	***
	Fruit Firmness (lb/inch^2) 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	4	0.144333333	0.0360833	0.0939161	0.9816	ns
Main	2	61.77633333	30.888167	80.394317	0.0000	***
Main Plot Error	8	3.073666667	0.3842083	—	—	—
Sub	3	84.476	28.158667	92.881803	0.0000	***
Sub * Main	6	22.105	3.6841667	12.152281	0.0000	***
Error	36	10.914	0.3031667	—	—	—
Total	59	182.4893333	—	—	—	—
Model	23	171.5753333	7.4597971	24.606258	0.0000	***

	TSS% 2024					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	2	0.361667	0.180833	0.644874	0.5718	ns
Mian	2	40.631667	20.315833	72.448737	0.0007	***
Main Plot Error	4	1.121667	0.280417	—	—	—
Sub plots						
Sub	3	47.149722	15.716574	53.209718	0.0000	***
Sub × Mian	6	6.606111	1.101019	3.727586	0.0138	*
Error	18	5.316667	0.295370	—	—	—
Total	35	101.187500	—	—	—	—
Model	17	95.870833	5.639461	19.092845	0.0000	***
	TSS% 2025					
Source	df	Type III SS	MS	F	P-value	Sig.

Main Plots						
Blocks	2	0.3267	0.1633	0.4404	0.6716	ns
Main	2	36.0650	18.0325	48.6270	0.0016	**
Main Plot Error	4	1.4833	0.3708	—	—	—
Sub Plots						
Sub	3	37.7719	12.5906	68.8850	0.0000	***
Sub × Main	6	2.8506	0.4751	2.5993	0.0541	ns
Error	18	3.2900	0.1828	—	—	—
Total	35	81.7875	—	—	—	—
Model	17	78.4975	4.6175	25.2629	0.0000	***

	Total sugars % 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	1.071088889	0.5355444	9.2059687	0.0319	*
Mian	2	54.53787222	27.268936	468.75096	0.0000	***
Main Plot Error	4	0.232694444	0.0581736	—	—	—
Sub	3	40.89526667	13.631756	33.018442	0.0000	***
Sub * Mian	6	12.86768333	2.1446139	5.1946214	0.0029	**
Error	18	7.43135	0.4128528	—	—	—
Total	35	117.0359556	—	—	—	—
Model	17	109.6046056	6.4473297	15.616535	0.0000	***
	Total sugars % 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.175555556	0.0877778	0.1629706	0.8550	ns
Main	2	43.80055556	21.900278	40.66065	0.0022	**
Main Plot Error	4	2.154444444	0.5386111	—	—	—
Sub	3	49.01555556	16.338519	41.055375	0.0000	***
Sub × Main	6	5.646111111	0.9410185	2.3645882	0.0733	ns
Error	18	7.163333333	0.397963	—	—	—
Total	35	107.9555556	—	—	—	—
Model	17	100.7922222	5.9289542	14.898256	0.0000	***

	Reduced Sugars % 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.255905556	0.1279528	0.1734643	0.8467	ns
Main	2	39.50857222	19.754286	26.780681	0.0048	**
Main Plot Error	4	2.950527778	0.7376319	—	—	—
Sub	3	31.61049722	10.536832	38.776106	0.0000	***
Sub * Main	6	7.628694444	1.2714491	4.6790005	0.0049	**
Error	18	4.891233333	0.2717352	—	—	—
Total	35	86.84543056	—	—	—	—
Model	17	81.95419722	4.8208351	17.740931	0.0000	***

	Reduced sugars % 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.66905	0.334525	0.7502944	0.5288	ns
Mian	2	33.63406667	16.817033	37.718334	0.0025	**
Main Plot Error	4	1.783433333	0.4458583	—	—	—
Sub	3	38.25496667	12.751656	83.322471	0.0000	***
Sub * Mian	6	4.575666667	0.7626111	4.9830896	0.0036	**
Error	18	2.754716667	0.1530398	—	—	—
Total	35	81.6719	—	—	—	—
Model	17	78.91718333	4.6421873	30.3332	0.0000	***

	Non-reduced Sugars % 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.35555	0.177775	0.172257	0.8477	ns
Mian	2	1.227616667	0.6138083	0.5947563	0.5941	ns
Main Plot Error	4	4.128133333	1.0320333	—	—	—
Sub	3	1.306963889	0.4356546	1.0600944	0.3905	ns
Sub * Mian	6	0.771161111	0.1285269	0.3127491	0.9220	ns
Error	18	7.39725	0.4109583	—	—	—
Total	35	15.186675	—	—	—	—
Model	17	7.789425	0.4582015	1.1149585	0.4095	ns
	Non-reduced sugars % 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.786938889	0.3934694	0.2388447	0.7980	ns
Mian	2	0.707622222	0.3538111	0.2147712	0.8155	ns
Main Plot Error	4	6.589544444	1.6473861	—	—	—
Sub	3	0.867411111	0.289137	0.9451125	0.4396	ns
Sub * Mian	6	1.127222222	0.1878704	0.6140985	0.7163	ns
Error	18	5.506716667	0.3059287	—	—	—
Total	35	15.58545556	—	—	—	—
Model	17	10.07873889	0.592867	1.9379254	0.0868	ns

	Carotene content (mg/100 g) 2024					
Source	df	SS	MS	F	P-value	Sig.
Main Plots						
Blocks	2	0.027839	0.013919	3.8150	0.1183	ns
Main	2	8.042739	4.021369	1102.1644	0.0000	***
Main Plot Error	4	0.014594	0.003649	—	—	—
Sub	3	8.126344	2.708782	85.1669	0.0000	***
Sub × Main	6	1.304306	0.217384	6.8348	0.0007	***
Error	18	0.572500	0.031806	—	—	—
Model	17	17.515822	1.030343	32.3950	0.0000	***

Total	35	18.088322	—	—	—	—
	Carotene content (mg/100 g) 2025					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	2	0.043838889	0.0219194	2.0995078	0.2380	ns
Mian	2	6.840022222	3.4200111	327.57856	0.0000	***
Main Plot Error	4	0.041761111	0.0104403	—	—	—
Sub	3	8.541388889	2.8471296	76.217034	0.0000	***
Sub × Mian	6	1.215911111	0.2026519	5.4249455	0.0023	**
Error	18	0.672400000	0.0373556	—	—	—
Total	35	17.35532222	—	—	—	—
Model	17	16.68292222	0.9813484	26.27048	0.0000	***

	Chlorophyll (mg/100 g) 2024					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	2	0.034955556	0.0174778	1.5969543	0.3092	ns
Mian	2	12.19602222	6.0980111	557.17868	0.0000	***
Main Plot Error	4	0.043777778	0.0109444	—	—	—
Sub plots						
Sub	3	17.394100000	5.7980333	119.48321	0.0000	***
Sub × Mian	6	1.720733333	0.2867889	5.9100137	0.0015	**
Error	18	0.873466667	0.0485259	—	—	—
Total	35	32.26305556	—	—	—	—
Model	17	31.38958889	1.8464464	38.05072	0.0000	***
	Chlorophyll (mg/100 g) 2025					
Source	df	Type III SS	MS	F	P-value	Sig.
Main Plots						
Blocks	2	0.184016667	0.0920083	2.6464525	0.1853	ns
Mian	2	20.29621667	10.148108	291.8919	0.0000	***
Main Plot Error	4	0.139066667	0.0347667	–	–	–
Sub	3	21.67194167	7.2239806	305.96882	0.0000	***
Sub × Mian	6	3.084450000	0.5140750	21.773442	0.0000	***
Error	18	0.424983333	0.0236102	–	–	–
Total	35	45.800675	–	–	–	–
Model	17	45.37569167	2.6691583	113.05114	0.0000	***

	Vitamin C (mg/100 mL) 2024					
Source	df	Type III SS	MS	F-value	P-value	Sig.
Main Plots						
Blocks	2	0.035972222	0.0179861	1.4233898	0.3413	ns
Mian	2	2.939372222	1.4696861	116.30842	0.0003	***
Main Plot Error	4	0.050544444	0.0126361	—	—	—

Sub Plots						
Sub	3	3.685075000	1.2283583	58.521637	0.0000	***
Sub × Mian	6	0.544583333	0.0907639	4.3241872	0.0071	**
Error	18	0.377816667	0.0209898	—	—	—
Model	17	7.255547222	0.4267969	20.333524	0.0000	***
Total	35	7.633363889	—	—	—	—
	Vitamin C (mg/100 mL) 2025					
Source	df	Type III SS	MS	F-value	P-value	Sig.
Main Plots						
Blocks	2	0.009905556	0.0049528	0.1070132	0.9010	ns
Mian	2	1.871022222	0.9355111	20.213306	0.0081	**
Main Plot Error	4	0.185127778	0.0462819	—	—	—
Sub Plots						
Sub	3	2.140988889	0.7136630	42.270264	0.0000	***
Sub × Mian	6	1.278111111	0.2130185	12.617089	0.0000	***
Error	18	0.303900000	0.0168833	—	—	—
Model	17	5.485155556	0.3226562	19.110930	0.0000	***
Total	35	5.789055556	—	—	—	—

	Fruit weight (g) 2024					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	4	0.400626667	0.1001567	0.1377376	0.9636	ns
Mian	2	95.58012333	47.790062	65.721936	0.0000	***
Main Plot Error	8	5.817243333	0.7271554	—	—	—
Sub	3	134.9997333	44.999911	77.987608	0.0000	***
Sub × Mian	6	25.75507667	4.2925128	7.4391881	0.0000	***
Error	36	20.77249	0.5770136	—	—	—
Total	59	283.3252933	—	—	—	—
Model	23	262.5528033	11.415339	19.783484	0.0000	***
	Fruit weight (g) 2025					
Source	df	Type III SS	MS	F	P	Sig.
Main plots						
Blocks	4	2.35485	0.5887125	1.2120814	0.3772	ns
Mian	2	83.13665333	41.568327	85.583705	0.0000	***
Main Plot Error	8	3.88563	0.4857037	—	—	—
Sub	3	106.6232	35.541067	42.200269	0.0000	***
Sub × Mian	6	25.0770	4.179500	4.962598	0.0009	***
Error	36	30.3192	0.842200	—	—	—
Total	59	251.3965333	—	—	—	—
Model	23	221.0773333	9.612058	11.413035	0.0000	***

	Flesh fruit weight (g) 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	4	0.250226667	0.0625567	0.082706	.9854	ns
Main	2	89.12132333	44.560662	58.913516	.0000	***
Main Plot Error	8	6.050993333	0.7563742	—	—	
Sub	3	127.2357533	42.411918	76.567863	.0000	***
Sub * Main	6	24.82003667	4.1366728	7.4680942	.0000	***
Error	36	19.94086	0.5539128	—	—	
Total	59	267.4191933	—	—	—	
Model	23	247.4783333	10.759928	19.42531	.0000	***
	Flesh fruit weight 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	4	2.157076667	0.5392692	1.0942814	0.4214	ns
Mian	2	80.05436333	40.027182	81.22289	0.0000	***
Main Plot Error	8	3.942453333	0.4928067	—	—	—
Sub	3	102.23108	34.077027	40.388292	0.0000	***
Sub * Mian	6	25.05265	4.1754417	4.948758	0.0009	***
Error	36	30.37447	0.8437353	—	—	—
Total	59	243.8120933	—	—	—	—
Model	23	213.4376233	9.2798967	10.998588	0.0000	***

	Flesh-fruit ratio 2024					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	0.696419398	0.1741048	0.2331566	0.9120	ns
Mian	2	4.169281622	2.0846408	2.7916963	0.1203	ns
Main Plot Error	8	5.973832637	0.7467291	—	—	—
Sub	3	8.061741107	2.687247	8.4188869	0.0002	***
Sub * Mian	6	2.45117329	0.4085289	1.2798818	0.2910	ns
Error	36	11.49093633	0.3191927	—	—	—
Total	59	32.84338439	—	—	—	—
Model	23	21.35244805	0.9283673	2.9084856	0.0020	**
	Flesh-fruit ratio 2025					
Source	df	Type III SS	MS	F	P	Sig
Blocks	4	0.558652313	0.1396631	1.1760949	0.3901	ns
Mian	2	6.813635179	3.4068176	28.688619	0.0002	***
Main Plot Error	8	0.950012305	0.1187515	—	—	—
Sub	3	8.459363723	2.8197879	15.113696	0.0000	***
Sub * Mian	6	3.471991004	0.5786652	3.1015699	0.0149	*
Error	36	6.716581187	0.1865717	—	—	—
Total	59	26.97023571	—	—	—	—
Model	23	20.25365452	0.8805937	4.7198674	0.0000	***

	Fruit length (cm) 2024					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.000555556	0.00027778	0.7968127	0.5114	ns
Main (Mian)	2	0.442405556	0.2212028	634.5259	0.0000	***
Main Plot Error	4	0.001394444	0.00034861	—	—	—
Sub	3	0.465430556	0.1551435	50.422811	0.0000	***
Sub * Main	6	0.035261111	0.0058769	1.9100211	0.1342	ns
Error	18	0.055383333	0.0030769	—	—	—
Total	35	1.000430556	—	—	—	—
Model	17	0.945047222	0.055591	18.067497	0.0000	***
	Fruit length (cm) 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.024938889	0.0124694	2.2955766	0.2168	ns
Main	2	0.467755556	0.2338778	43.055996	0.0020	**
Main Plot Error	4	0.021727778	0.0054319	—	—	—
Sub	3	0.524777778	0.1749259	44.683065	0.0000	***
Sub * Main	6	0.055155556	0.0091926	2.3481552	0.0749	ns
Error	18	0.070466667	0.0039148	—	—	—
Total	35	1.164822222	—	—	—	—
Model	17	1.094355556	0.0643739	16.443653	0.0000	***

	Fruit diameter (cm) 2024					
Source	df	Type III SS	MS	F	P	Sig
Blocks	2	0.001438889	0.00071944	0.1256062	0.8853	ns
Mian	2	0.331705556	0.1658528	28.955868	0.0042	**
Main Plot Error	4	0.022911111	0.0057278	—	—	—
Sub	3	0.304008333	0.1013361	33.134423	0.0000	***
Sub * Mian	6	0.055916667	0.0093194	3.0472298	0.0309	*
Error	18	0.05505	0.0030583	—	—	—
Total	35	0.771030556	—	—	—	—
Model	17	0.715980556	0.0421165	13.771064	0.0000	***
	Fruit diameter (cm) 2025					
Source	df	Type III SS	MS	F	P	Sig.
Blocks	2	0.0026	0.0013	7.0909	0.0484	*
Mian	2	0.308116667	0.1540583	840.31818	0.0000	***
Main Plot Error	4	0.000733333	0.0001833	—	—	—
Sub	3	0.340733333	0.1135778	40.563492	0.0000	***
Sub * Mian	6	0.051616667	0.0086028	3.0724206	0.0299	*
Error	18	0.0504	0.0028	—	—	—
Total	35	0.7542	—	—	—	—
Model	17	0.7038	0.0414	14.785714	0.0000	***