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The Role of Some Biostimulants in Improving the Productivity of Orange

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Abstract: One of the environmental problems that affects negatively orange productivity is drought because it greatly minimizes the growth attributes, photosynthetic process, water uptake, percentage of fruit set, and productivity; meanwhile, it raises the rates of respiration and transpiration, as well as the premature and preharvest fruit drop percentages. In addition, drought creates osmotic stress, affects the relationship between plants and water, reduces the amount of water in shoots, and prevents plant cell development and expansion. It is very important to search for a solution to minimize the effect of drought stress; therefore, the present study has investigated the effect of the application of humic acid (HA) at 0, 1 and 2 kg per tree and spraying of seaweed extract (SWE) at 0.2, 0.3 and 4% in combination with moringa leaf extract (MLE) at 2, 4 and 6%, respectively, on the productivity, fruit quality and nutritional status of navel orange cv. Washington during the 2022 and 2023 seasons. The results proved that the application of the biostimulants individually or in combination significantly positively changed the vegetative growth, productivity, fruit quality parameters and leaf mineral content of macro- and micronutrients of the treated trees compared to untreated trees. The superior treatments which gave the best results were 2 kg HA + 0.4% SWE + 6% MLE followed by 2 kg HA + 0.3% SWE + 4% MLE over the rest of the applied treatments.

Keywords: *Moringa oleifera*; seaweed extract; fruit drop; nutritional status

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1. Introduction

The increasing frequency and severity of climate events have heightened constraints on plant performance, leading to reduced crop productivity and quality [1]. Zhang et al. [2] reported that abiotic stressors are currently the main factor responsible for large plant yield losses, which can range from 50% to 80%, depending on the crop and the region. The productivity of tree crops is often limited by adverse weather conditions, insufficient crop nutrition, inadequate pollination, premature fruit drop, and low-quality fruit [3,4]. As the intensity and duration of drought stress increase, net photosynthesis, stomatal conductance, transpiration rate, and intracellular carbon dioxide concentration decrease [5,6]. Brodribb and McAdam [7] suggest that plants can endure water stress by reducing their stomatal conductance to minimize water loss and by developing more efficient root systems to enhance water absorption [8].

Citrus is considered the greatest fruit crop worldwide, as it occupies approximately 18% of the total fruit crop area in the world, where the area is 10.1 million hectares, which produces 166 million tones; meanwhile, the cultivated area of citrus in Egypt is ≈209 hectares, which produces 4.751 million tons. Specifically, the cultivated area of orange is 143.376 hectares and produces ≈3.393 million tons [9], and the most area in Egypt is cultivated by "Washington" navel orange (*Citrus sinensis* (L.) Osbeck), which is planted mainly for exporting for fresh consumption because of its attractive colors, unique scents, and delectable tastes, as well as its high nutritional content and health-improving properties [10,11].

Plant biostimulants are substances used to improve plants' nutrient availability, absorption, and efficiency. They enhance growth, yield, quality, and tolerance to abiotic and biotic stresses [12]. Using biostimulants can effectively and sustainably meet plants' nutrient needs, serving as an alternative to mineral fertilizers. They help address environmental issues linked to excessive mineral fertilization under water stress [13,14] and induce the activity of key enzymes involved in carbon and nitrogen metabolism, as well as hormone activity, such as auxin and gibberellin [15]. Additionally, biostimulants can enhance the photosynthetic rate, stomatal conductance, and transpiration rate, while boosting plants' carbon assimilation efficiency [16].

HA increases the growth and development of the root system, consequently raising the levels of water and nutrient absorption, thereby enabling plants to withstand environmental stressors [17]. The application of HA to the soil positively improves the membrane permeability of plant roots [18], encouraging the uptake of nutrients, enhancing metabolic processes, encouraging the beneficial soil microbiota [19], and boosting protein production and potential hormone-like functions [20]. HA also provides beneficial indirect effects, including reducing nitrogen loss and improving soil properties such as its overall formation and stability, total porosity, reduced pH levels, efficient permeability, and retention of water and nutrients [19,21]. HAs have been shown to be a functional additive for preserving soil quality and enhancing the efficacy of fertilizers [22]. HAs affect soil properties, both physical and chemical, such as permeability and water reservation power. They also stimulate root system development, enhancing enzyme activity and increasing nutrient uptake and soil fertility [23].

Moringa leaf extract (MLE) is easy to prepare, cost-effective, environmentally friendly, and widely used by farmers as a biostimulant to boost growth and productivity in various crops [24]. Furthermore, MLE serves as a great substitute for organic fertilizers because of its high content of essential amino acids and minerals [25], essential mineral nutrients, vitamins, proteins, carbohydrates, sugars, free proline, and free amino acids [26,27]. *Moringa oleifera* leaves are rich in high-content nutrients because they are rich in minerals, vitamins, β-carotene, and phenolic acids [28]. The application of MLEs could stimulate the defense system and increase tolerance in plants against abiotic stresses [29]. Moreover, the presence of phytohormones in MLE greatly increases cell division and elongation, thereby boosting plant growth and yield [30].

Seaweed extract (SWE) has numerous positive impacts on plants since it contains high quantities of auxins and cytokines [31]. Additionally, Thomas et al. [32] documented that SWE contains high quantities of cytokinin, gibberellins, abscisic acid, ethylene and auxins, which increase plant tissue growth and cell division. Additionally, it was reported that SWE contains high quantities of microelements and plant growth hormones that have a positive impact on encouraging bloom induction to improve the flower rates of the crops [33]. SWEs are rich in phytohormones [34], and their spraying increases growth and productivity and fruit quality characteristics in grapes [35] and improves nutrient use [36,37]. SWE is distinguished by its substantial content of minerals, organic matter and plant growth regulators; therefore, foliar application of it on fruit trees is an effective method to raise growth, photosynthesis, total soluble solids (TSS), yield and fruit quality [38–40]. This study was conducted during two seasons, 2022 and 2023, to investigate the possibility of depending on the use of biostimulants on "Washington" navel orange to reduce the dependency on chemical fertilizers.

2. Materials and Methods

2.1. Site and Applied Treatments

This study was conducted in Nubaria Region, Behaira Governorate, Egypt, on 10-year-old "Washington" navel oranges budded on Volkameriana rootstock during 2022–2023.

2.2. The Applied Biostimulants

The orange trees were fertilized with 100% water-soluble humic acid (Shandong Aminuo Fertilizer Co., Ltd., Anqiu City, Weifang, Shandong, China) at 0, 1 and 2 kg per tree in February 2022 and 2023, and then the trees were sprayed with seaweed extract (SWE) at 0, 0.2, 0.3 and 0.4% (46.5% organic matter; 15.5% K_2O; 2.9% P_2O_5; 100% water solubility; ≥2% polyphenols; ≥300 ppm cytokinin and gibberellin; 0.6% microelements (Cu, Fe, Mn, Zn, B); 11–15% sugar alcohol; ≤5.0% moisture; 2.1% total nitrogen; ≥16% alginic acid; 100% solubility in water—Qingdao Sonef Chemical Co., Ltd., Qingdao, China) as well as moringa leaf extract (MLE) at 0, 2, 4 and 6%. The leaves of moringa were dried and were ground to a powder using a small laboratory mill, which was then soaked in distilled water for 48 h at room temperature. The mixture was filtered using Whatman No. 1 filter paper and the concentrations of 2%, 4%, and 6% were prepared [35].

The trees were sprayed three times: first before flowering in March, then during full bloom, and finally a month after the second spraying. The experiment was designed as a Split Plot with two factors: the main factor is soil application with HA, and the sub-main factor is foliar spraying with SWE + MLE. Table 1 presents the analysis of the test soil [41], and the weather data in Table 2 was collected according to [42].

Table 1. The analysis of experimental soil.

Season	Sand%	Silt%	Clay%	Textural Class	Organic Matter %	pH	$CaCO_3$%	EC (dS/m)
2022	56.3	22	21.7	Sandy loam	0.45	8.00	4.85	1.95
2023	54.55	24.8	20.65	Sandy loam	0.61	7.80	4.75	1.85

Season	Soluble Anions (meq/L)			Soluble Cations (meq/L)				Available Nutrients (mg/kg) Macronutrients			Available Nutrients (mg/kg) Micronutrients		
	HCO_3^-	Cl^-	SO_4^{--}	Ca^{++}	Mg^{++}	Na^+	K^+	N	P	K	Fe	Zn	Mn
2022	9.80	4.50	5.18	7.20	5.46	4.02	3.22	128	14	205	2.1	0.37	1.8
2023	9.52	4.11	5.30	7.50	4.90	3.90	3.25	130	19	213	2.5	0.4	1.9

Table 2. Weather data during the 2022 and 2023 seasons.

Year	2022				2023			
Months	Minimum Temperature (°C)	Maximum Temperature (°C)	Average Relative Humidity (%)	Precipitation (mm)	Minimum Temperature (°C)	Maximum Temperature (°C)	Average Relative Humidity (%)	Precipitation (mm)
January	9.20	16.66	71.30	72.10	11.89	20.35	72.73	31.70
February	9.65	18.19	71.32	14.50	10.61	18.87	68.77	48.70
March	9.84	18.93	67.50	61.10	12.75	23.43	63.57	19.00
April	13.98	27.70	58.60	0.70	14.39	26.33	59.06	16.00
May	17.27	30.54	60.45	3.80	17.36	30.53	59.56	0.40
June	21.44	34.72	61.80	1.20	20.98	35.63	60.92	2.40
July	22.82	37.01	61.45	2.10	23.70	37.93	61.01	0.00
August	24.06	38.35	61.56	0.60	24.36	38.00	60.61	0.00
September	23.07	33.34	60.56	1.10	24.05	34.80	60.11	0.60
October	20.48	28.77	62.91	3.00	21.30	30.15	65.05	4.30
November	16.99	24.41	63.58	2.70	18.05	26.89	63.62	5.00

The above-mentioned treatments were tested by studying their influences on the following parameters:

2.3. Vegetative Growth Parameters

At the end of the vegetative period, the shoot length and diameter in centimeters were measured using a vernier caliper. Total chlorophyll content (SPAD) was determined in fresh leaves by taking 10 readings from the mature leaves from each replicate.

2.4. Fruit Set %, Fruit Drop % and Fruit Number

The total number of flowers at full bloom in May and then the number of set fruits were reordered for both years of study, and then the fruit set percentages were calculated using Equation (1).

$$\text{Fruit set \%} = \frac{No.of\ set\ fruits}{No.of\ flowers} \times 100 \quad (1)$$

The fruit drop percentage was calculated by Equation (2).

$$\text{Fruit drop } (\%) = \frac{No.of\ fruitlets\ at\ initial\ set\ -\ No.of\ harvested\ fruits}{No.of\ fruitlets\ at\ initial\ set} \times 100 \quad (2)$$

2.5. Fruit Yield (ton/ha)

Fruit Yield (ton/ha) was assessed by multiplying the weight of fruits/tree × number of trees/ha.

2.6. Fruit Quality

2.6.1. Physical Fruit Quality

Fruit length and diameter were measured by using a Digital Vernier caliper. The weights of fruit were measured by taking the average weight of 10 fruits. Fruit volume (cm^3) was assessed by the weight of the removed water by using a graduated cylinder of 1000 mL containing tap water. Fruit firmness was expressed as kg/cm^2 by using a Magness Taylor pressure tester.

2.6.2. Chemical Fruit Quality

Total soluble solids (TSS %) in the juice of fruits were measured by using a hand refractometer (ATAGO, Tokyo, Japan). Total acidity (%) was determined as citric acid/100 milliliters of fruit juice [43]. The phenol–sulfuric acid method was used to estimate the total sugars by using 1.0 mL of sample treated with 1.0 mL of 5% phenol and 5.0 mL of concentrated H_2SO_4 and measured at 485 nm. Reduced sugars were estimated by using the 3,5-dinitro salicylic acid (DNS) method by using 2.0 mL of the sample and 1.5 mL of DNS at 80 °C for 10 min and measuring at 510 nm [44]. The content of ascorbic acid was determined by titration using 2,6-dichloro phenol indophenol [45]. Fruit carotene content was measured using the method of [46] at a wavelength of 440 nm.

2.7. Nutritional Status

After harvesting the fruits in the 2022 and 2023 seasons, 40 leaves from the middle part of the shoots were collected from each tree [47]. After washing the leaves very well with tap water, they were washed again with distilled water, dried at 70 °C until constant weight and then ground and digested using H_2SO_4 and H_2O_2 until the solution became clear. The nitrogen content was determined using the micro Kjeldahl method [48]. The phosphorus content was measured using the Vanadomolybdo method [49]. The potassium content was determined using a flame photometer [50]. Atomic absorption spectrophotometry was used to measure the micronutrient content of Fe, Mn, Zn, and B.

2.8. Statistical Analysis

The results were analyzed statistically using a Split Plot Design with CoHort Software 6.311 (Pacific Grove, CA, USA). The least significant difference at 0.05% ($LSD_{0.05}$) was applied to compare the treatment means [51].

3. Results

Vegetative growth measurements, including shoot length, shoot diameter, and total leaf chlorophyll, were significantly enhanced by the soil application of HA at 1 and 2 kg on trees combined with the spraying of 0.2% SWE + 2% MLE, 0.3% SWE + 4% MLE and 0.4% SWE + 6% MLE (Table 3). The most obvious increments were notably obtained by the application of 2 kg of HA combined with the spraying of 0.4% SWE + 6% MLE over the other applied treatments. In addition, the application of 2 kg of HA was more effective than the application of 1 kg. Spraying with 0.4% SWE + 6% MLE was better than 0.3% SWE + 4% MLE, which was consequently higher than 0.2% SWE + 2% MLE.

Table 3. Effect of HA soil application and the spraying of SWE + MLE on the shoot length, shoot diameter and leaf total chlorophyll of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spray	Shoot Length (cm)		Shoot Diameter (cm)		Chlorophyll Content (SPAD)	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	9.14 g	9.45 e	0.11 f	0.12 c	71.54 d	71.24 e
	0.2% SWE + 2% MLE	9.22 g	9.75 de	0.11 f	0.13 bc	71.72 d	72.08 e
	0.3% SWE + 4% MLE	9.55 fg	10.10 de	0.12 def	0.13 bc	74.04 cd	74.92 cd
	0.4% SWE + 6% MLE	10.17 def	10.42 cd	0.13 cdef	0.14 bc	75.24 bc	76.80 bc
1 kg HA	0 SWE + 0 MLE	9.35 g	9.92 de	0.11 f	0.13 bc	73.78 cd	73.64 de
	0.2% SWE + 2% MLE	10.35 cde	10.52 cd	0.14 bcde	0.14 bc	75.40 bc	77.70 bc
	0.3% SWE + 4% MLE	10.77 bcde	11.02 bc	0.13 bcdef	0.14 bc	76.05 bc	78.32 b
	0.4% SWE + 6% MLE	10.92 bcd	11.17 bc	0.14 bcd	0.14 bc	76.65 bc	78.52 b
2 Kg HA	0 SWE + 0 MLE	10.07 ef	10.14 de	0.12 ef	0.13 bc	74.12 cd	76.54 bc
	0.2% SWE + 2% MLE	11.12 bc	11.42 b	0.15 bc	0.15 b	77.08 bc	78.84 b
	0.3% SWE + 4% MLE	11.35 b	11.55 b	0.15 b	0.15 b	78.25 b	79.41 b
	0.4% SWE + 6% MLE	12.02 a	12.32 a	0.17 a	0.17 a	80.88 a	82.66 a
$LSD_{0.05}$		0.58	0.57	0.01	0.02	2.34	2.34

No significant differences were observed between treatments that share the same letters in a column.

Fruit set percentages and fruit numbers were greatly increased by the soil application of HA at 1 and 2 kg/tree in combination with the spraying of 0.2% SWE + 2% MLE, 0.3% SWE + 4% MLE, and 0.4% SWE + 6% MLE compared to untreated trees (Table 4). Additionally, it was noticed that the soil addition of HA at 2 kg was more efficient in improving the fruit set percentages and fruit numbers rather than the application of 1 kg. On the other hand, the same mentioned treatments significantly reduced the fruit drop percentages. A highly positive effect was obtained by the soil addition of 2 kg of HA combined with the spraying of 0.4% SWE + 6% MLE.

Table 4. Effect of HA soil application and the spraying of SWE + MLE on the fruit set %, fruit drop % and fruit number of "Washington" navel orange during 2022 and 2023 seasons.

Soil Application	Foliar Spray	Fruit Set %		Fruit Drop %		Fruit Number	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	3.67 f	4.16 g	85.32 a	80.68 a	247.75 f	248.25 f
	0.2% SWE + 2% MLE	3.74 f	4.18 g	83.57 ab	79.56 ab	249.50 ef	248.50 f
	0.3% SWE + 4% MLE	4.18 de	4.42 efg	80.52 b	78.47 ab	251.50 ef	258.00 f
	0.4% SWE + 6% MLE	4.23 cde	4.55 def	75.44 c	74.76 cd	253.50 def	259.75 ef
1 kg HA	0 SWE + 0 MLE	4.06 e	4.30 fg	82.07 ab	79.69 ab	250.00 ef	252.00 f
	0.2% SWE + 2% MLE	4.31 bcd	4.65 de	75.42 c	73.53 cde	257.75 cde	270.75 de
	0.3% SWE + 4% MLE	4.36 bcd	4.77 cd	73.47 cd	72.78 cde	262.50 cd	274.75 cd
	0.4% SWE + 6% MLE	4.41 bc	4.93 bc	73.03 cd	71.61 def	264.00 c	275.75 cd
2 kg HA	0 SWE + 0 MLE	4.17 de	4.44 efg	79.80 b	76.38 bc	251.50 ef	255.25 f
	0.2% SWE + 2% MLE	4.44 bc	5.06 b	71.45 cd	70.77 ef	278.50 b	284.25 bc
	0.3% SWE + 4% MLE	4.50 b	5.11 b	71.44 cd	68.88 fg	285.75 b	291.00 b
	0.4% SWE + 6% MLE	4.73 a	5.40 a	70.14 d	66.98 g	305.25 a	309.25 a
$LSD_{0.05}$		0.15	0.23	3.93	3.50	8.83	11.31

No significant differences were observed between treatments that share the same letters in a column.

The results in Table 5 show that the fruit weight and fruit yields were significantly increased by the soil addition of HA at 1 and 2 kg for each tree, and the effect was greatly raised by the spraying of 0.2% SWE + 2% MLE, 0.3% SWE + 4% MLE and 0.4% SWE + 6% MLE. The highest positive influence was accompanied by the application of 2 kg of HA with 0.4% SWE + 6% MLE, which is the best treatment over the other applied treatments. The increment in the fruit yield gradually increased in parallel to raising the dose of HA, where 2 kg was better than 1 kg for each tree.

Table 5. Effect of HA soil application and the spraying of SWE + MLE on the fruit weight, and fruit yield of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spray	Fruit Weight (g)		Fruit Yield (kg/tree)		Yield (ton/h)	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	277.50 g	283.00 h	69.38 i	70.33 g	26.64 i	27.01 g
	0.2% SWE + 2% MLE	283.75 fg	285.25 h	70.74 i	71.88 g	27.16 i	27.60 g
	0.3% SWE + 4% MLE	290.50 ef	294.50 fg	71.97 ghi	75.99 f	27.63 ghi	29.18 f
	0.4% SWE + 6% MLE	294.75 de	304.50 e	77.37 ef	77.91 f	29.71 ef	29.92 f
1 kg HA	0 SWE + 0 MLE	281.25 g	291.50 g	71.36 hi	72.38 g	27.40 hi	27.79 g
	0.2% SWE + 2% MLE	300.00 cd	305.25 e	74.85 fg	82.44 e	28.74 fg	31.66 e
	0.3% SWE + 4% MLE	302.25 cd	313.25 d	77.91 de	86.07 d	29.92 de	33.05 d
	0.4% SWE + 6% MLE	305.75 bc	316.00 d	80.72 d	87.12 d	30.99 d	33.45 d
2 Kg HA	0 SWE + 0 MLE	291.75 e	298.00 f	73.95 gh	77.41 f	28.39 gh	29.72 f
	0.2% SWE + 2% MLE	302.50 cd	323.25 c	84.18 c	91.90 c	32.33 c	35.29 c
	0.3% SWE + 4% MLE	310.25 b	330.00 b	88.63 b	96.03 b	34.03 b	36.88 b
	0.4% SWE + 6% MLE	320.00 a	336.00 a	97.66 a	103.91 a	37.50 a	39.90 a
$LSD_{0.05}$		7.21	5.08	2.92	3.53	1.12	1.36

No significant differences were observed between treatments that share the same letters in a column.

The results in Table 6 show that fruit volume, fruit length and fruit diameter were significantly improved by the addition of HA whether it was added at 1 or 2 kg for each tree individually or in combination with the spraying of 0.2% SWE + 2% MLE, 0.3% SWE + 4% MLE and 0.4% SWE + 6% MLE during the experimental period. Additionally, raising the applied concentrations of MLE and SWE effectively increased the fruit volume, fruit length and fruit diameter compared to non-treated trees.

Table 6. Effect of HA soil application and the spraying of SWE + MLE on the fruit volume, fruit length, and fruit diameter of "Washington" navel orange during 2022 and 2023 seasons.

Soil Application	Foliar Spray	Fruit Volume (cm^3)		Fruit Length (cm)		Fruit Diameter (cm)	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	299.75 f	303.75 g	8.27 g	8.72 e	7.87 f	8.38 f
	0.2% SWE + 2% MLE	300.50 f	303.75 g	8.38 f	8.86 cde	8.00 e	8.42 ef
	0.3% SWE + 4% MLE	312.50 e	315.00 ef	8.43 ef	8.92 bcd	7.99 e	8.52 d
	0.4% SWE + 6% MLE	315.25 de	325.25 d	8.53 de	8.90 cde	8.12 d	8.49 de
1 kg HA	0 SWE + 0 MLE	302.25 f	312.50 f	8.40 f	8.79 de	7.92 ef	8.36 f
	0.2% SWE + 2% MLE	320.00 cd	325.00 d	8.57 d	8.98 bc	8.17 cd	8.47 de
	0.3% SWE + 4% MLE	322.75 c	334.50 c	8.64 d	9.09 b	8.22 c	8.48 de
	0.4% SWE + 6% MLE	325.00 bc	337.25 c	8.75 c	9.34 a	8.32 b	8.55 cd
2 Kg HA	0 SWE + 0 MLE	311.50 e	318.50 e	8.45 ef	8.95 bcd	8.10 d	8.53 d
	0.2% SWE + 2% MLE	324.00 bc	345.75 b	8.84 bc	9.38 a	8.34 b	8.64 b
	0.3% SWE + 4% MLE	330.50 b	350.25 b	8.92 b	9.39 a	8.40 ab	8.62 bc
	0.4% SWE + 6% MLE	341.25 a	356.50 a	9.15 a	9.51 a	8.46 a	8.73 a
$LSD_{0.05}$		6.52	5.31	0.11	0.16	0.09	0.08

No significant differences were observed between treatments that share the same letters in a column.

The addition of HA to the soil at 1 and 2 kg solely improved the fruits' characteristics in terms of fruit firmness, fruit carotene and fruit juice percentages throughout the study seasons (Table 7). The spraying of 0.2% SWE + 2% MLE, 0.3% SWE + 4% MLE, and 0.4% SWE + 6% MLE also significantly improved the same measured fruit characteristics. The influence of the applied treatments of HA soil application or spraying of MLE + SWE was greatly increased with the combination. The greatest increases were achieved with the application of 2 kg of HA along with the spraying of 0.4% SWE + 6% MLE in the two seasons, followed by 2 kg of HA with 0.3% SWE + 4% MLE.

Table 7. Effect of HA soil application and the spraying of SWE + MLE on the fruit firmness and fruit content of carotene and juice as a percentage of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spray	Fruit Firmness (kg/cm^2)		Carotine (mg/100 g)		Juice %	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	0.94 g	0.96 f	3.13 g	3.19 g	47.31 e	48.05 h
	0.2% SWE + 2% MLE	0.96 fg	1.01 ef	3.22 efg	3.24 fg	50.40 d	50.65 g
	0.3% SWE + 4% MLE	1.03 de	1.03 de	3.28 defg	3.37 efg	51.57 d	53.38 ef
	0.4% SWE + 6% MLE	1.13 c	1.09 cd	3.33 cdef	3.44 de	52.23 cd	54.87 cde
1 kg HA	0 SWE + 0 MLE	1.01 ef	1.01 ef	3.18 fg	3.31 efg	51.56 d	51.57 fg
	0.2% SWE + 2% MLE	1.14 bc	1.14 bc	3.37 bcde	3.41 def	52.02 cd	55.05 cde
	0.3% SWE + 4% MLE	1.14 bc	1.16 ab	3.41 abcd	.45 de	54.79 bc	55.61 bcd
	0.4% SWE + 6% MLE	1.19 ab	1.20 ab	3.43 abcd	3.59 d	56.29 ab	56.05 bc
2 kg HA	0 SWE + 0 MLE	1.07 d	1.07 cde	3.30 def	3.45 de	52.50 cd	53.75 de
	0.2% SWE + 2% MLE	1.20 a	1.22 a	3.47 abc	3.83 c	56.67 ab	56.60 bc
	0.3% SWE + 4% MLE	1.22 a	1.21 a	3.51 ab	4.11 b	57.06 ab	57.26 b
	0.4% SWE + 6% MLE	1.23 a	1.23 a	3.56 a	4.30 a	58.81 a	59.85 a
$LSD_{0.05}$		0.05	0.06	0.15	0.18	2.64	1.91

No significant differences were observed between treatments that share the same letters in a column.

The fruit content of soluble solids and vitamin C was greatly improved by the usage of HA on the soil at 2 or 1 kg for each tree compared to not trees, and at the same time, it was greatly increased by the spraying of MLE + SWE rather than unsprayed trees during the experimental period (Table 8). The impact of the combination of HA soil application with the spraying of MLE + SWE was more efficient in raising the fruit content of TSS and VC rather than the individual application of each of them. The most significant increments were noticed with the application of 2 kg of HA mixed with 0.4% SWE + 6% MLE, followed by 2 kg of HA + 0.3% SWE + 4% MLE. Conversely, when compared to the control, the same applied treatments decreased the fruit acidity.

The results demonstrated in Table 9 show that the soil addition of HA or the spraying of MLE + SWE individually or in combination improved the fruit content of total, reduced and non-reduced sugars percentages compared to the control. The most significant increments were noticed by the application of 2 kg of HA combined with the spraying with 0.4% SWE + 6% MLE, 0.3% SWE + 4% MLE and 0.2% SWE + 2% MLE, respectively, in the two seasons. Sugar fruit content gradually increased in parallel to raising the amount of HA and also by raising the concentration of SWE + MLE, even if they were used individually or in combination.

The results in Tables 10 and 11 show that the addition of HA to the soil or the spraying of SWE + MLE individually or in combination significantly improved the leaf content of macro- and micronutrients compared to non-treated trees. In addition, the best leaf mineral contents of N, P, K, Fe, Mn, Zn and B were noticed with the application of 2 kg HA + 0.4% SWE + 6% MLE, which gave the highest increments. The results also showed the application of 2 kg HA + 0.3% SWE + 4% MLE, followed by 2 kg HA + 0.2% SWE + 2% MLE compared to non-treated trees greatly raised the mineral content. Increasing the sprayed concentrations of MLE + SWE or increasing the amount of HA in the trees was more successful in enhancing the mineral content of the leaves.

Table 8. Effect of HA soil application and the spraying of SWE + MLE on the fruit content of TSS %, acidity % and vitamin C of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spraying	TSS %		Acidity %		VC (mg/100 mL)	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	11.92 f	12.20 g	2.00 a	1.90 a	40.20 d	41.00 g
	0.2% SWE + 2% MLE	12.25 e	12.37 fg	1.89 ab	1.82 ab	40.27 d	41.25 fg
	0.3% SWE + 4% MLE	12.32 de	12.55 def	1.78 bc	1.75 bcd	42.50 cd	43.50 def
	0.4% SWE + 6% MLE	12.40 de	12.70 cdef	1.75 bcd	1.68 cdef	43.00 c	44.25 cde
1 kg HA	0 SWE + 0 MLE	12.27 de	12.45 efg	1.78 bc	1.78 bc	42.50 cd	42.25 efg
	0.2% SWE + 2% MLE	12.42 cde	12.77 bcde	1.71 cde	1.65 defg	43.50 bc	45.25 cd
	0.3% SWE + 4% MLE	12.60 bcd	12.82 abcd	1.68 cdef	1.63 defg	45.00 abc	45.75 cd
	0.4% SWE + 6% MLE	12.72 bc	12.87 abcd	1.60 def	1.62 efg	45.50 ab	46.25 bc
2 Kg HA	0 SWE + 0 MLE	12.37 de	12.70 cdef	1.76 bcd	1.73 bcde	42.75 c	44.00 cde
	0.2% SWE + 2% MLE	12.75 ab	12.90 abc	1.55 ef	1.61 efg	45.75 ab	48.25 ab
	0.3% SWE + 4% MLE	12.82 ab	13.05 ab	1.51 f	1.57 fg	45.87 ab	48.75 a
	0.4% SWE + 6% MLE	13.05 a	13.12 a	1.51 f	1.53 g	46.25 a	49.25 a
$LSD_{0.05}$		0.30	0.31	0.15	0.11	2.29	2.25

No significant differences were observed between treatments that share the same letters in a column.

Table 9. Effect of HA soil application and the spraying of SWE + MLE on the fruit content of total, reduced and non-reduced sugars percentages of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spraying	Total Sugars %		Reduced Sugars %		Non Reduced Sugars %	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	9.01 e	9.46 h	5.26 e	5.65 g	3.75 d	3.81 c
	0.2% SWE + 2% MLE	9.06 e	9.85 gh	5.27 e	5.78 fg	3.78 d	4.08 bc
	0.3% SWE + 4% MLE	9.72 d	9.88 gh	5.44 de	6.14 de	4.28 bc	3.74 c
	0.4% SWE + 6% MLE	9.84 d	10.34 efg	5.55 d	6.31 d	4.29 bc	4.13 bc
1 kg HA	0 SWE + 0 MLE	9.55 d	9.87 gh	5.31 e	5.94 ef	4.23 bcd	3.93 bc
	0.2% SWE + 2% MLE	9.90 d	10.59 def	6.03 c	6.59 c	3.87 cd	4.12 bc
	0.3% SWE + 4% MLE	10.33 c	10.81 cde	6.12 c	6.72 c	4.20 bcd	4.21 abc
	0.4% SWE + 6% MLE	10.52 c	11.05 bcd	6.15 c	6.96 b	4.37 abc	4.26 abc
2 kg HA	0 SWE + 0 MLE	9.762 d	10.10 fg	5.61 d	6.15 d	4.15 bcd	4.06 bc
	0.2% SWE + 2% MLE	10.93 b	11.33 bc	6.61 b	7.08 b	4.32 bc	4.39 abc
	0.3% SWE + 4% MLE	11.28 b	11.62 b	6.77 b	7.11 b	4.52 ab	4.67 ab
	0.4% SWE + 6% MLE	11.89 a	12.21 a	7.07 a	7.33 a	4.83 a	4.88 a
$LSD_{0.05}$		0.38	0.56	0.18	0.20	0.44	0.65

No significant differences were observed between treatments that share the same letters in a column.

Table 10. Effect of HA soil application and the spraying of SWE + MLE on the leaf mineral content of nitrogen, phosphorous and potassium of "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spraying	N %		P %		K %	
		2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	1.41 h	1.53 i	0.30 h	0.39 g	1.38 f	1.40 g
	0.2% SWE + 2% MLE	1.45 h	1.55 i	0.33 gh	0.40 fg	1.38 f	1.41 g
	0.3% SWE + 4% MLE	1.59 f	1.66 gh	0.40 f	0.43 ef	1.40 f	1.46 ef
	0.4% SWE + 6% MLE	1.61 ef	1.73 ef	0.43 ef	0.47 d	1.48 de	1.50 de
1 kg HA	0 SWE + 0 MLE	1.52 g	1.62 h	0.35 g	0.42 efg	1.40 f	1.42 fg
	0.2% SWE + 2% MLE	1.68 de	1.74 ef	0.45 de	0.48 d	1.50 de	1.52 d
	0.3% SWE + 4% MLE	1.70 cd	1.79 de	0.48 cd	0.52 c	1.53 d	1.61 c
	0.4% SWE + 6% MLE	1.75 c	1.84 cd	0.48 cd	0.54 bc	1.56 cd	1.65 c

Table 10. *Cont.*

Soil Addition	Foliar Spraying	N %		P %		K %	
		2022	2023	2022	2023	2022	2023
2 kg HA	0 SWE + 0 MLE	1.60 f	1.70 fg	0.40 f	0.45 de	1.45 ef	1.50 de
	0.2% SWE + 2% MLE	1.83 b	1.88 c	0.50 c	0.55 bc	1.62 c	1.72 b
	0.3% SWE + 4% MLE	1.87 b	1.94 b	0.55 b	0.58 b	1.69 b	1.76 b
	0.4% SWE + 6% MLE	1.95 a	2.01 a	0.59 a	0.61 a	1.77 a	1.84 a
$LSD_{0.05}$		0.06	0.06	0.03	0.03	0.07	0.05

No significant differences were observed between treatments that share the same letters in a column.

Table 11. Effect of HA soil application and the spraying of SWE + MLE on the leaf mineral content of iron, zinc, manganese and boron in "Washington" navel orange during 2022 and 2023 seasons.

Soil Addition	Foliar Spraying	Fe ppm		Zn ppm		Mn ppm		B ppm	
		2022	2023	2022	2023	2022	2023	2022	2023
Zero HA	0 SWE + 0 MLE	143.50 g	146 g	40.25 g	43.25 g	38.00 g	41.00 h	44.00 f	43.50 h
	0.2% SWE + 2% MLE	146.75 f	149.5 f	41.25 fg	44.00 g	38.50 g	41.25 h	45.50 ef	45.50 gh
	0.3% SWE + 4% MLE	148.75 f	150 f	44.75 e	47.50 efg	40.00 g	45.90 fg	47.00 e	47.75 fg
	0.4% SWE + 6% MLE	152.75 e	156.5 d	46.50 de	48.75 ef	46.25 ef	47.50 f	50.75 d	50.00 ef
1 kg HA	0 SWE + 0 MLE	147.25 f	150.75 f	43.75 ef	45.75 fg	39.50 g	42.75 gh	46.00 ef	47.00 fg
	0.2% SWE + 2% MLE	156.75 d	159 d	47 de	50.25 de	48.00 de	50.50 e	51.00 d	51.75 de
	0.3% SWE + 4% MLE	157.00 d	165 c	47.75 de	52.75 cd	50.25 cd	52.50 de	54.00 c	54.00 cd
	0.4% SWE + 6% MLE	161.75 c	162.75 c	49.25 d	54.25 c	50.75 cd	54.50 cd	53.25 cd	55.00 c
2 kg HA	0 SWE + 0 MLE	148.75 f	153.5 e	45.25 e	45.50 fg	43.50 f	44.50 fgh	47.25 e	47.75 fg
	0.2% SWE + 2% MLE	159.75 cd	164.5 c	53.00 c	56.00 c	53.00 c	56.75 bc	58.25 b	58.50 b
	0.3% SWE + 4% MLE	168.5 b	172.25 b	56.75 b	59.25 b	56.00 b	59.15 b	59.00 b	60.25 b
	0.4% SWE + 6% MLE	173.5 a	176 a	61.75 a	62.50 a	60.25 a	62.75 a	62.50 a	63.50 a
$LSD_{0.05}$		2.80	2.57	2.77	3.02	2.95	2.86	2.07	2.67

No significant differences between the treatments that have the same letters in one column.

4. Discussion

From the obtained results, HA positively improved the experimental soil composition, which consequently reflected in improving the growth, productivity, fruit quality and nutritional status of orange. This was previously confirmed by the findings of several authors, who noted that using HAs enhanced the soil combined index by raising soil aeration, porosity, and preservation of nutrients, while they reduced the soil bulk density [52] and preserved water, dissolved soil, absorbed solar heat, and encouraged the growth of microorganisms and plants [53]. Additionally, HA plays a crucial role in ameliorating the rates of stomatal conductance, chlorophyll synthesis, respiration, and photosynthesis, consequently improving the metabolism of sugars and amino acids as well as raising plant resistance to abiotic stresses by increasing cell wall thickness [54,55]. The vegetative growth and fruit dimensions of orange were improved after the application of the soil addition of HA, and this was formerly explained by Trevisan et al. [56], who showed that this stems from HA hormone-like activity or an IAA-independent mechanism that promotes cell elongation and division, balances hormones like cytokinin, accumulates proline as an osmotic agent, and promotes leaf cell elongation and division [57]. HA is an organic fertilizer that has the ability to raise the intake of nutrients like N, P, K, Ca, Mg, Fe, Zn, Mn and B [58]; therefore, it improves plant growth [59,60], fruit set percentage, fruit yield and fruit quality as well as nutritional status [61,62] by forming complexes with soil cations [20,63]. In addition, HA induces morphogenesis, lateral root establishment, root hair initiation, and root and shoot development; enhances nutrient utilization efficiency; and improves the metabolism of carbon and nitrogen [20,64]. The application of HA to grapevines increased berry size by enhancing mineral nutrient uptake, and its effect appeared similar to that of auxin, gibberellin, and cytokinin-like activity [65]. Applying HA to soil at rates of 0.5, 1, and 2 kg per tree improved the concentration of chlorophyll in the leaves, number of flowers, fruit set percentages, productivity, weight, dimensions of fruits, firmness, soluble solid content, and leaf mineral content of NPK in olive. Additionally, it reduced fruit drop percentages, with the 2 kg application being the most effective compared to untreated trees [66].

The positive influence of MLE on the growth and productivity of plants returns to its high content of essential minerals like sulfur, zinc, copper, iron, selenium, nitrogen, potassium, calcium, magnesium, and phosphorous, as well as amino acids, carbohydrates, proteins, vitamins [67–69], and hormones, including salicylic acid, jasmonic acid, auxins, and gibberellins [70,71]. Although abiotic stress lowers cytokinin levels in plants, reducing growth and productivity [72], MLE serves as an efficient source of cytokinins, zeatin and phenols; therefore, it mitigates the impacts of drought stress more effectively, enhancing chlorophyll content, increasing cell division and elongation, improving water intake, proportional water content, and water use efficacy, minimizing leaf senescence, preserving photosynthetic activity, and enhancing growth and physiological and biochemical processes [73,74]. In addition, it also improves gas exchange, carotenoids, stomatal conductance, flowering, floral traits, fruiting, yield, and fruit quality [75,76]. The existence of ABA in MLE perhaps elevates proline and antioxidant levels in treated plants, thereby protecting them from osmotic stress and sustaining physiological processes [77,78]. The exogenous application of a Flame Seedless grape cultivar with 2, 4, and 6% MLE notably improved the shoot length, shoot thickness, chlorophyll content in leaves, productivity, and fruit quality measurements compared to untreated trees [35]. Spraying Kalamata olive trees with 6% MLE greatly improved the chlorophyll concentration in the leaves, the number of flowers, the fruit set, the fruit yields, the oil content in the fruits, the fruit firmness, the soluble solid contents, and the nutrient concentrations in the leaves under salinity stress [79].

The positive impact of SWE on improving the performance of "Washington" navel orange trees under study was explained by numerous authors. They stated that SWE is rich in vitamins, amino acids, organic matter, and saccharides; promoting hormones like auxins, gibberellins, cytokinins, and polyamines; macronutrients such as phosphorous, potassium, magnesium, and calcium; and micronutrients such as copper, iron, manganese, and zinc. Therefore, they can activate the physiological processes in plants such as plant development, as well as blooming and yielding, improving the nutritional content and fruit shelf life, and surviving abiotic stresses such as drought, salinity, and cold [80–83]. By increasing the number and surface area of roots under drought stress as well as the density and length of roots, the application of SWE encouraged the growth of roots in deep soil and enhanced water absorption and utilization [84,85] and lessened the effects of drought on the cell membrane, as well as raising plant biomass [86]. Applying SWE at concentrations of 3 and 4 g/L enhanced shoot length and diameter, leaf chlorophyll, fruit set, productivity, and various fruit advantages including weight, size, TSS%, sugars, and nutritional content. Additionally, it lessened fruit acidity in guava compared to the control over two seasons [87]. Spraying kiwi vines with 1, 2 and 3 g/L SWE at the fruit set and 10 days from the fruit set improved the fruit contents of soluble solids, sugars, and ascorbic acid; meanwhile, it lessened the physiological loss of weight, and the usage of 3 g/L was superior [88]. The application of SWE at 0.4% on date palm cv. Samani greatly improved the palm yield, fruit, seed and flesh weights, fruit volume, fruit dimensions, fruit firmness, soluble solids, total and reduced sugars, vitamin C and total chlorophyll in the fruits [89].

5. Conclusions

The soil addition of HA and the foliar spraying of SWE + MLE solely or in combination improved the vegetative growth parameters, yield, fruit quality characteristics and leaf mineral content of macro- and micronutrients compared to control. The application of 2 kg HA + 0.4% SWE + 6% MLE was the superior treatment which gave the best results over the other applied treatments. Additionally, the application of 2 kg HA + 0.3% SWE + 4% MLE also positively improved the performance of "Washington" navel orange trees.

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