Mesopotamia Journal of Agriculture

https://magrj.mosuljournals.com

INFLUENCE OF NANO SILICON AND SEAWEED EXTRACT APPLICATIONS ON GROWTH AND FRUITING OF YOUNG LIME TREES (*Citrus aurantifolia* Swingle) UNDER SANDY SOIL CONDITIONS

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Article information
Article history:
Received: 18/01/2024
Accepted: 21/03/2024
Published: 31/03/2024

Keywords:
Acid lime, fruit quality, nano silicon, seaweed extract, yield.

DOI:
https://doi.org/10.33899/mja.2024.146188.1351

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ABSTRACT

A two-year experimental study was conducted during the 2021 and 2022 seasons on 3-year-old acid lime (*Citrus aurantifolia* Swingle) trees budded on Volkamer Lemon rootstock grown in sandy soil under a drip irrigation system in the El Nubaria region, Behera Governorate, Egypt. The study aims to investigate the effect of foliar spraying with three concentrations of both seaweed extract (0, 2, and 4 ml.L^{-1}) and nano-silicon (0, 1, and 1.5 ml.l^{-1}) on the growth and productivity of lime trees, which arranged in a randomized complete block design with three replicates for each treatment, and each replicate was represented by one tree. The obtained results showed that foliar sprays of seaweed extract combined with nano-silicon enhanced tree vigor, leaf mineral content, number of fruits per tree, total yield, and fruit quality. Combinations of nano-silicon (1 ml) and seaweed extract (4 ml) proved to be the most efficient treatment for enhancing most studied growth parameters during the experiment and achieved yield productivity of 23.09 and 15.31 % greater than the control. In conclusion, the above results showed that foliar application of nano-silicon with seaweed extract could have beneficial influences on growth and tree yield and improve the fruit quality of immature lime trees.

INTRODUCTION

Acid lime trees (*Citrus aurantifolia* Swingle) have a high economic value and are considered one of the most important fruit crops worldwide, ranking as the third citrus fruit around the world after orange and mandarin. Lime cultivation has become more interesting in Egypt in the past few years due to its high profitability. Therefore, the cultivated area reached 40,826 feddan, with a fruiting area of about 36618 feddan and an average yield of 10.015 t per feddan. Lime production is concentrated in Nubaria, Wadi El Mulak, some regions of Assiut and Sohag governorates, and some areas of the Delta region, while it covers 14084 feddan in Nubaria, accounting for over 34% of the total lime cultivation area. Nubaria District is one of the major lemon-producing areas in Egypt (Annual Reports of the Statistical Institute and Agricultural Economic Research in Egypt, 2022).

It is well documented that there is a positive correlation between citrus productivity and adequate fertilization, which is an important factor in sustaining citriculture. A lack of nutrients could also limit the growth and economic production of citrus orchards (Bastakoti, *et al., 2022*; Zoremtluangi, *et al*., 2019).

One of the management practices, such as a foliar spray of seaweed extract and silicon, can improve the growth, yield, and fruit quality of fruit trees (Matthews, *et al.,* 2022).

Silicon (Si) is the second most abundant element in soils, however, it is considered a semi-essential component, particularly for dicotyledons. Although Si improves plant growth and plays an important role in the regulation of physiological mechanisms in fruit trees (Hassan, *et al.*, 2022). Since silicon plays an important role in plant nutrition, and enhances the plant's ability to tolerate environmental stress, protects cells from metal toxicity, enhances the activity of certain enzymes, and increases the soluble components of the plant xylem (Souri, *et al.*, 2021).

Nanofertilizers reach a specific site in a plant faster and achieve a rapid reaction with more efficiency (Abobatta, 2023). Using Nano-fertilizers to control nutrient release is a powerful tool for stimulating plant growth and enhancing fertilizer use efficiency. There is great potential for nanotechnology in the agricultural field, like nano fertilizers, nano pesticides, nanosensors, etc., It also sustains the environment by reducing the regular application of bulk fertilizers, moreover, nano-fertilizers should improve nutrient supplies (Abobatta, 2023; Ul Ain, *et al.*, 2018; Guo, *et al.*, 2018). The effect of silicon nanoparticles (Si-NPs), which are characterized by their small size, high reactivity, and surface area, on the physiology of fruit trees must be evaluated (Laane, 2018).

Furthermore, previous reports have mentioned the positive effects of nanosilicon in improving the growth and productivity of various fruit trees, such as those by Hassan *et al*., (2022) on olive trees, El-Dengawy, *et al.*, (2021) and Elsheery, *et al.,* (2020) on mango trees; Abo El-Enein, *et al.,* (2019) on navel orange trees; Ashkavand, *et al., (*2018) on Prunus cherry.

Seaweed extract is considered one of the natural biostimulants that promote plant growth due to its higher content of various components such as organic content, some nutrients, some phytohormones, polyamines, proteins, vitamins, etc. (Hassan, *et al.,* 2021).

Therefore, the stimulating effect of seaweed extract may be due to its various components, which improve the absorption of nutrients and thus stimulate the growth of various plant organs (Ali, *et al.*, 2021). Seaweed extract can be exploited to achieve higher crop yields and reduce fertilizer consumption. Several studies have evoked the stimulating activity of seaweed extracts (Yao, *et al*., 2020). The studies reveal that seaweed extracts and their components have very significant potential for improving plant growth and productivity (Al-Saif, *et al.*, 2023).

To the best of the authors' knowledge, this is considered one of the few studies to cover goals, and the first is on using Si NPs and SE to stimulate immature lime trees under Egyptian conditions. So, the topic of this study was to estimate the sensible effects of foliar sprays of nano-silicon and seaweed extract, which might improve the vegetative growth, nutritional status, and fruiting of immature lime trees (*Citrus aurantifolia* Swingle) under sandy soil conditions.

MATERIALS AND METHODS

Twenty-seven uniform trees were selected randomly to carry out the investigation, each tree was taken as an experimental unit, all selected trees were randomly tagged according to the treatment, and the randomized complete block design was settled with nine treatments with three replications per treatment.

The selected trees were three years old, as nearly uniform in size as possible, and free from infestations and diseases. The selected trees were grafted on the Volkamer lemon (*Citrus volkameriana*) rootstock, planted at 5 x 5 meters apart (160 trees.feddan^{-1}) three years ago before the study, while the rootstock was planted 10 years before. The old cultivar was removed in 2018 and grafted with Acid Lime (*Citrus aurantifolia* Swingle) at the same time. The collection of lime specimens has been done with the permission of the private landowner.

Nano silicon particles (Si-NPs) were prepared and characterized in the radiation research department of the National Center for Radiation Research and Technology, Atomic Energy Authority, Cairo, Egypt. Si-NPs were prepared at concentrations of (control, water only), 1.5, and 2 ml.L^{-1}.

Seaweed Extract was prepared at three rates (control, water only), 2, and 4 ml.L^{-1}, and the interaction of both substances was applied as foliar applications two times in mid-March and mid-July each season at a rate of 3 L of water for each tree or replicate. Triton-B as a wetting agent was applied at 0.05% to all spraying solutions, and spraying was done until runoff (20 l/tree). The control trees were sprayed with tap water and Triton B only. Spraying was done until runoff. Other practice management was done under the instructions of the Ministry of Agriculture.

Treatments that were used in the experiment were

T1: Control (spraying with water)
T2: Nano Silicon (1 ml.L^{-1}) {Si-NPs 1}
T3: Nano Silicon (1.5 ml.L^{-1}) {Si-NPs 2}
T4: Seaweed Extract (2 ml.L^{-1}) {SE1}
T5: Seaweed Extract (4 ml.L^{-1}) {SE2}
T6: Nano Silicon (1 ml.L^{-1}) + Seaweed Extract (2 ml.L^{-1}) {Si-NPs 1+ SE1}
T7: Nano Silicon (1 ml.L^{-1}) + Seaweed Extract (4 ml.L^{-1}) {Si-NPs 1+ SE2}
T8: Nano Silicon (1.5 ml.L^{-1}) + Seaweed Extract (2 ml.L^{-1}) {Si-NPs2+ SE1}
T9: Nano Silicon (1.5 ml.L^{-1}) + Seaweed Extract (4 ml.L^{-1}) {Si-NPs2+ SE2}

Eight non-fruiting spring shoots were selected randomly and tagged in May every year, and the length of each shoot was measured in September to determine the average shoot length. Growth data were collected at the end of September annually and included tree canopy (m^3), leaf dry matter (%), and leaf chemical composition by relying on a sample of 10 full-size leaves collected randomly from the middle part of tagged non-fruiting spring growth cycle shoots of each experimental unit (Arrobas, *et al.*, 2018).

To determine leaf mineral content, leaf samples were washed with tap water, then with distilled water, dried at 70 ^oC finely ground, and digested. The digested solution was used to determine N, P, K, Si, Fe, Mn, and Zn content.

At harvesting time, the number of fruits collected from each tree was tallied and weighed to obtain the average weight of tree yield. Tree yield was calculated by using a formula given below and expressed in kilograms (kg) per tree.

- $Yield\ (kg.tree-1)\ =\ (Number\ of\ fruits\ per\ tree\ x\ Fruit\ weight\ in\ g)/\ 1000.$
- $Consequently, the\ total\ yield\ (ton.feddan-1) was\ computed\ hypothetically.$
- $Fruit\ yield\ increment\ or\ reduction\ percentage\ was\ calculated\ by\ the\ equation\ of\ (Hifny, et\ al., 2017), whereas, fruit\ yield\ increment\ or\ reduction\ (\%)\ =$

$$\frac{\text{Fruit yield (kg)/treatment} - \text{Fruit yield (kg)/ control X 100}}{\text{Fruit yield (kg)/ control}}$$

Fruit physical and chemical properties

Ten mature fruits were randomly picked from each tree, and the studied parameters involved physical and chemical characteristics, for instance, fruit weight (g), juice ratio (w/w %), and TSS were determined by a handy Refractometer and expressed as Brix. Titratable acidity percentage in fruit juice was estimated as g citric acid per 100 ml of juice by titration against 0.1 N sodium hydroxide in the presence of phenol phthalin as an indicator, according to AOAC (2000); thus, the TSS/acid ratio was calculated. Ascorbic acid (vitamin C) content (mg per 100 ml of juice) was determined by titration against 2, 6-dichlorophenol indophenol (mg per 100 ml) following the method illustrated in the AOAC (Horwitz & Latimer 2005) and expressed as mg/100 mg of juice.

Soil analysis

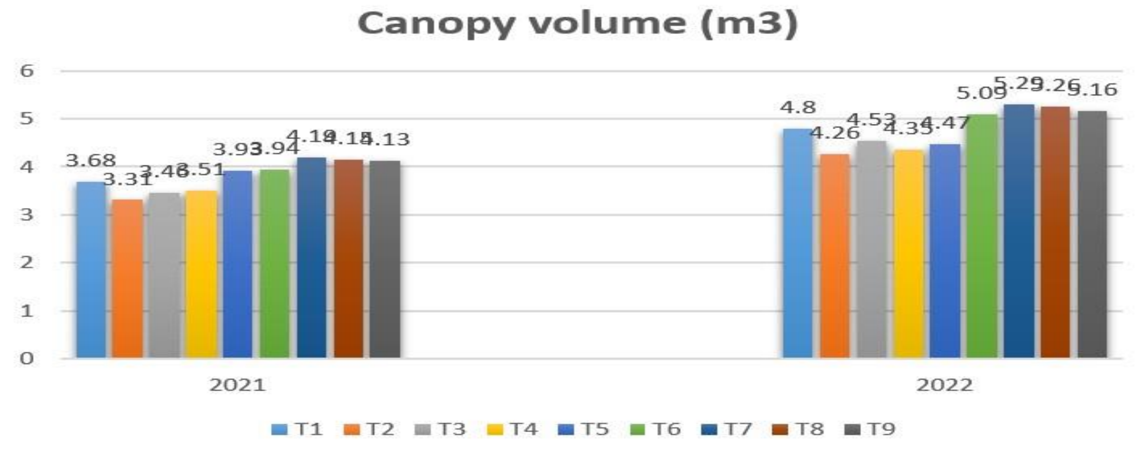
Soil samples were taken from the study site at two depths (0–30 cm and 30–60 cm) before starting the experiment to determine the physical and chemical properties, according to Page, (1982).

Table (1): Soil physical and chemical properties of the site soil

Depth	0-30 cm	30-60 cm
Particle size distribution %		
Sand	92.42	94.56
Silt	3.38	2.37
Clay	4.20	3.07
Texture class	Sandy	Sandy
pH	8.18	8.07
EC (ds/m)	1.35	1.19
Soluble cations meq. L^{-1}		
K	0.53	3.84
Ca	3.50	4.85
Mg	4.42	0.49
Na	5.11	2.77
Soluble Anions meq. L^{-1}		
$CO3^{--}$	0.00	0.00
$HCO3^{-}$	3.82	6.51
Cl^{-}	3.23	3.00
$SO4^{--}$	6.51	2.44

RESULTS AND DISCUSSION

Regarding tree growth parameters, significant effects were found for the Si-NPs and SE extract combinations compared to individual treatments, which produced less vegetative growth. While trees that were subjected to a combination of Si-NPs and SE applications grew more vigorously than individual treatments of both SI-NPs and/or SE treatments in both seasons. As shown in Figure (1) plants that received T7 recorded the maximum canopy volume (4.19 & 5.29 m^3), followed by Si-NPs (1.5 $ml.L^{-1}$) + SE (2 $ml.L^{-1}$) which recorded (4.15 & 5.26 m^3). On the contrary, the low rate of Si-NPs treatment recorded the lowest significant value of tree canopy (3.31 & 4.26 m^3) during the experiment.



*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

Figure (1): Effect of foliar application of Nano Si and seaweed extract on vegetative growth and macro elements contents of lime trees

Regarding leaf dry matter percentage, data in Table (2A) showed that various treatments caused a significant increase compared to control treatments during the experimental seasons. Foliar application of a combination of low rates of both substances led to increased dry matter and tree growth. Whereas, T7 recorded the maximum value (63.48 & 72.46 %) in both seasons, followed by T8, which recorded (62.13& 68.76 %), while the lowest dry matter (57.52 & 52.95%) was recorded with T2.

Mineral composition of leaves was affected by various treatments of Si-NPs, SE, and their combinations. As for the effect of various treatments, as displayed in Tables (2 A&B), it is obvious that all studied leaf chemical constituents didn't follow the same response trend to the nano-silicon and seaweed extract sprays compared to the control (water spray). Some leaf element content followed an exact trend, for instance, N and K followed a consistent trend in response to the treatments, where such leaf chemical components were increased significantly by the treatments compared to the control. Herein, as far as the leaf N and Mn contents were concerned, the (1 $ml.L^{-1}$ Si-NPs + 4 $ml.L^{-1}$ SE) treatment was superior for both seasons.

As stated previously, there is a positive effect of most treatments on nitrogen leaf content, except T2, which recorded the lowest N content (1.977 %) in the first season, and T4 (2.043%) in the second one, whereas T7 recorded the highest values

(2.483 & 2.497 %) during the experiment. While, as for leaf K % content, T9 was the most effective statistically during the experimental seasons and recorded the highest values of K % leaf content (1.680 & 1.663 %) compared to other treatments.

Table (2 A): Effect of foliar application of Nano Si and seaweed extract on the leaf chemical composition of lime trees

Treatment	Leaves dry matter (%)		N (%)		P (%)		K (%)	
	2021	2022	2021	2022	2021	2022	2021	2022
T 1	57.85 G	62.98 F	2.113 CD	2.137 DE	0.156 A	0.150 A	1.360 E	1.540 CD
T 2	57.52 H	52.95 H	1.977 D	2.053 E	0.123C	0.124C	1.500 D	1.623 AB
T 3	59.94 E	65.45 E	2.037 D	2.117 E	0.125C	0.128BC	1.540 CD	1.513 D
T 4	58.69 F	60.24 G	2.007 D	2.043 E	0.127BC	0.128BC	1.300 F	1.377 E
T 5	60.56 D	63.01 F	2.089 CD	2.097 E	0.128BC	0.129BC	1.400 E	1.570 BC
T 6	61.23 C	66.69 D	2.211 BC	2.237 CD	0.141A-C	0.140A-C	1.590 BC	1.347 E
T 7	63.48 A	72.46 A	2.483 A	2.497 A	0.127BC	0.128BC	1.630 AB	1.287 F
T 8	62.13 B	68.76 B	2.237 BC	2.287 BC	0.149A	0.148A	1.560 C	1.517 CD
T 9	62.04 B	66.74 C	2.330 AB	2.367 B	0.145AB	0.147AB	1.680A	1.663A

*Values in the same column followed by the same letter(s) do not significantly differ according to Duncan's multiple range test at 5% level.

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

On the contrary, the response of leaf P % to a specific effect of Si-NPs and SE treatments went the other way around. Whereas all applications resulted in redaction below control, which recorded the highest values (0.156 & 0.150 %), followed by T8 (0.149 &0.148 %), while the low rate of Si-NPs recorded the lowest values (0.123 & 0.124 %) in both seasons.

On the contrary, the response of leaf P % to a specific effect of Si-NPs and SE treatments went the other way around. Whereas all applications resulted in redaction below control, which recorded the highest values (0.156 & 0.150 %), followed by T8 (0.149 &0.148 %), while the low rate of Si-NPs recorded the lowest values (0.123 & 0.124 %) in both seasons.

Data in Table (2 B) indicated that foliar application of Si-NPs greatly improves the absorption of Fe Zn by plant tissues and increases the micro-elements in the leaves of lime trees. Regarding Mn leaf content, T7 recorded the highest values (49.19 & 48.69 mg kg-1), followed by T6 (48.31 & 47.78 mg kg-1), while untreated trees have the lowest values (32.71 & 32.08 mg kg-1). The combination of higher rates of both applied substances (T9) recorded the highest Si leaf content (0.875 &0.899 Si m mol g^{-1} Dw), while the high rate of SE (T5) recorded the lowest values approximately (0.436 & 0.424 Si m mol g^{-1} Dw).

Table (2 B): Effect of foliar application of Nano Si and seaweed extract on the leaf chemical composition of lime trees

Treatment	Fe mg kg^{-1}		Zn mg kg^{-1}		Mn mg kg^{-1}		Si m mol g^{-1} Dw	
	2021	2022	2021	2022	2021	2022	2021	2022
T 1	63.51 GH	64.62 D	33.31 DE	33.30 D	32.71 I	32.08 E	0.459 C	0.501 D
T 2	63.60 G	63.48 D	31.70 E	30.42 E	35.31 H	34.62 D	0.716 B	0.7660 C
T 3	62.77 H	63.86 D	38.59 BC	37.53 C	40.39 E	40.10 B	0.842 AB	0.887 AB
T 4	69.03 E	65.92 CD	38.80 BC	37.73 C	42.19 C	41.50 B	0.441 C	0.459 D
T 5	68.18 F	69.85 BCD	36.13 CD	38.13 C	38.41 F	37.71 C	0.436 C	0.424 D
T 6	71.58 D	71.99ABC	43.15 A	44.22 A	48.31 B	47.78 A	0.809 AB	0.783 BC
T 7	72.70 C	74.23 AB	40.93 AB	41.83 B	49.19 A	48.69 A	0.812 AB	0.830 ABC
T 8	76.13 A	78.03 A	37.33 C	38.33 C	41.31 D	41.38 B	0.858 AB	0.886 AB
T 9	74.33 B	75.31 AB	36.06 CD	37.26 C	36.29 G	36.91 C	0.875 A	0.899 A

*Values in the same column followed by the same letter(s) do not significantly differ from each other according to Duncan's multiple range test at 5% level.

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

Si-NPs and SE alone or in combinations significantly affected all the studied yield parameters, i.e., fruit weight, yield per tree, total yield, and yield efficiency, which varied due to treatments.

Our results in Tables (3 and 4) showed that all the yield-stated measured parameters except the fruit volume from trees subjected to a low rate of Si-NPs with a higher rate of SE treatment (T7) recorded the highest significant values of tree yield, yield per feddan, fruit weight, and yield efficiency. The lowest yield parameter values were recorded in the control trees (T1) in both seasons, except for yield efficiency in the second season. Furthermore, lime yield differed slightly from the first season to the second one.

It was noted that the application of a combination of Si-NPs and SE had shown better fruit yield than individual treatments of both Si-NPs or/and SE. Yield of trees treated with a low rate of Si-NPs and a higher rate of SE was much higher than that of control and other treatments due to the increased formation of dry matter and availability of nutrients. Thus, T7 produced the maximum tree yield (10.09, & 11.64 kg.tree^{-1}) when applied, followed by T8 (9.88 & 11.57 Kg.tree^{-1}) in both seasons. On the other hand, untreated trees (T1) produced the lowest tree yield (7.40 & 9.02 Kg.tree^{-1}), and there are variations in the impact of other treatments on tree yield during experimental seasons. The carried-out treatments significantly affected total yield, whereas T7 produced the maximum yield (1.66 & 1.92 ton.feddan^{-1}), followed by T8 (1.63 & 1.91 tons.feddan^{-1}), while untreated tress (T1) produced the lowest total yield (1.22 & 1.49 ton.feddan^{-1}).

Table (3): Effect of foliar application of Nano Silicon and seaweed extract on yield parameters of lime trees

Treatment	Tree yield (Kg.tree^{-1})		Total yield (Ton. feddan^{-1})		Yield Efficiency		Yield increment %	
	2021	2022	2021	2022	2021	2022	2021	2022
T 1	7.40 I	9.02 E	1.22 G	1.49 E	2.23 DE	2.13 A	0.00 CD	0.00 C
T 2	8.21 F	10.10 C	1.35 E	1.67 C	2.24 DE	2.11 A	-9.89 D	-10.71 E
T 3	7.78 H	9.72 CD	1.28 F	1.60 CD	2.26 CD	2.15 A	-5.10 D	-3.81 CD
T 4	7.97 G	9.32 DE	1.31 EF	1.54 DE	2.28 CD	2.16 A	-2.79 CD	-7.73 DE
T 5	8.60 E	9.61 D	1.42 D	1.59 D	2.19 E	2.17 A	4.58 BCD	-4.81 D
T 6	9.06 D	11.08 B	1.50 C	1.83 B	2.30 C	2.20 A	10.74 ABC	9.740 B
T 7	10.09 A	11.64 A	1.66 A	1.92 A	2.41 A	2.22 A	23.09 A	15.31 A
T 8	9.88 B	11.57 A	1.63 AB	1.91 AB	2.38 AB	2.19 A	20.87A	14.54 A
T 9	9.710 C	11.24 AB	1.60 B	1.85 AB	2.35 B	2.18 A	18.69 AB	11.26 AB

*Values in the same column followed by the same letter(s) do not significantly differ from each other according to Duncan's multiple range test at 5% level.

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

Concerning the impact of treatments on yield increment compared with the control, the tabulated data in Table (3) showed that T7 caused the highest increment (23.09 & 15.31%), followed by T8 (20.87 & 14.54%), and T2 recorded the highest reduction in both seasons (-9.89 & -10.71%).

Considering the impact of Si-NPs and SE treatments on fruit characters, it can be said that trees subjected to T7 had greater values compared to other treatments.

The effect on fruit quality was not as large with individual treatment of Si-NPs or SE. Therefore, foliar spray of combinations of the highest doses of both substances led to significant improvements in fruit quality, i.e. fruit weight, fruit density, juice ratio, TSS, TSS/Acidity ratio, and vitamin C.

Tabulated data in Table (4 A and B) clarifies that T7 produced the heaviest fruit (30.51 & 31.52 g), followed by T8 (30.36 & 29.91 g), and the control treatment recorded the lowest value (24.62 g) in the first season and T2 (26.00 g) in the second one, respectively. Applicable treatments statistically increased fruit volume compared to control. The lower dose of SE (T4) recorded the biggest fruit volume and achieved the highest significant values (29.36 & 28.83 cm^3) when applied, followed by T9 (27.63 & 28.17 ml). Contrarily, the smallest fruit volume (20.02 cm^3) was produced from untreated trees (T1) in the first seasons and from T2 (21.17 cm^3) in the second one.

Trees subjected to T5 and T9 in the first season produced the maximum fruit number (337) per tree compared to other treatments, while T7 had the highest values (512.3) in the second one. On the contrary, T3 recorded the least fruit number (291.0) in the first season and T5 (438.7) in the second one had the minimum fruit number compared to other treatments.

Regarding the effect of various treatments on juice weight, data in Table (4A) cleared that, across seasons, trees subjected to T7 produced the highest juice weight (21.45 &22.47 g), followed by T8 (19.88 & 19.82 g), while T2 recorded the lowest value (13.99 g) in the first season and untreated trees (T1) in the second one (14.84 g), respectively.

Concerning to the findings, lime fruits grow more after receiving various treatments. Data in Table (4A) showed that trees subjected to T7 produced juicy fruits and had the highest juice ratio values (70.22 & 71.34 %), followed by T9 (68.08 %) in the first season and T8 (66.22%) in the second one, while the control treatment recorded the lowest values (55.84 & 56.49 %).

Table (4 A): Effect of foliar application of Nano Silicon and seaweed extract on fruit physical characters of lime trees

Treatment	Fruit weight (g)		Fruit Volume (cm^3)		Fruit number.Tree^{-1}		Juice Weight (g). Fruit^{-1}		Juice Ratio	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T 1	24.62 G	26.29 B	20.02 I	23.00 AB	306.3 E	501.3 C	14.98 DE	14.84F	55.84G	56.49 G
T 2	26.80 D	26.00 B	23.54 G	21.17 B	300.7 F	503.0 BC	13.99 F	15.11F	57.57E	58.15 F
T 3	26.73 D	26.40 B	25.49 E	25.17 AB	291.0 H	480.0 E	15.26 D	15.55E	57.06E	59.04 E
T 4	26.63 E	26.20 B	29.36 A	28.83 A	299.3 G	462.7 F	14.88 DE	15.21EF	55.91FG	58.05 F
T 5	25.58 F	26.13 B	27.34 C	28.00 AB	337.0 A	438.7 H	14.39 EF	15.21EF	56.73EF	58.40 F
T 6	28.83 C	28.59 AB	25.67 D	25.50 AB	314.3 D	451.7 G	17.38 C	17.38D	60.46D	60.82 D
T 7	30.51 A	31.52 A	24.85 F	25.67 AB	330.3 B	512.3 A	21.45 A	22.47A	70.22A	71.34 A
T 8	30.36 B	29.91 A	21.26 H	21.00 B	325.7 C	484.7 D	19.88 B	19.82B	65.50C	66.22 B
T 9	28.79 C	29.46 A	27.63 B	28.17 AB	337.0 A	504.7 B	19.27 B	18.83C	68.08B	64.51 C

*Values in the same column followed by the same letter(s) do not significantly differ according to Duncan's multiple range test at 5% level.

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

Data in Table (4B) showed that, across seasons, TSS values from trees subjected to T7 represented the significantly highest values (9.74 & 9.83), followed by T8 (9.70 & 9.33), while T2 recorded the lowest TSS (8.37 & 8.40) in both seasons.

Regarding the effect of treatments on fruit acidity, data in our hands cleared that most treatments reduced acidity compared to the control treatment except T2, which recorded the highest values (16.03%) in the first season and the control treatment (16.37%) in the second one, while, T6 recorded the lowest values (13.76 & 13.62 %).

Table (4 B): Effect of foliar application of Nano Silicon and seaweed extract on fruit physical characters of lime trees

Treatment	TSS		Acidity (%)		Vitamin C (mg.100g^{-1})	
	2021	2022	2021	2022	2021	2022
T 1	8.61D	8.50 BC	14.77 D	16.37 A	20.02 B	21.17 B
T 2	8.37 F	8.40 C	16.03 A	15.10 B	23.54 AB	23.00 AB
T 3	8.52 E	8.67 BC	15.10 B	14.75 BC	25.49 AB	25.17 AB
T 4	8.39 F	8.47 BC	14.37 F	14.43BCD	27.63 AB	28.17 AB
T 5	8.77 C	8.77 BC	14.87 C	14.72 BC	27.34 AB	28.00 AB
T 6	8.50 E	8.67 BC	13.76 H	13.62 D	25.67 AB	25.50 AB
T 7	9.74 A	9.83 A	14.27 G	13.99 CD	24.85 AB	25.67 AB
T 8	9.70 B	9.33 AB	14.70 E	14.09 CD	21.26 B	21.00 B
T 9	9.50 B	9.17 ABC	14.77 D	14.70 BC	29.36 A	28.83 A

*Values in the same column followed by the same letter(s) do not significantly differ from each other according to Duncan's multiple range test at 5% level.

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

Concerning the impact of used treatments on vitamin C, tabulated data in Table (4B) indicates that T9 has the highest value (29.36 & 28.83), followed by T4 (27.63 & 28.17), while untreated trees recorded the lowest values (20.02 & 21.17) during both seasons. According to Figure (2), data clearly showed that all treatments affected positively the TSS/Acidity ratio across seasons, whereas trees subjected to T7 recorded the highest significant value (0.68 & 0.70%), followed by those under T8 (0.66 & 0.65%). Although the control treatment has the lowest values (0.54 & 0.52%), while there were fluctuating responses to other treatments during the experiment. While, lowest values were recorded from trees subjected to T4 (0.940 & 0.937).

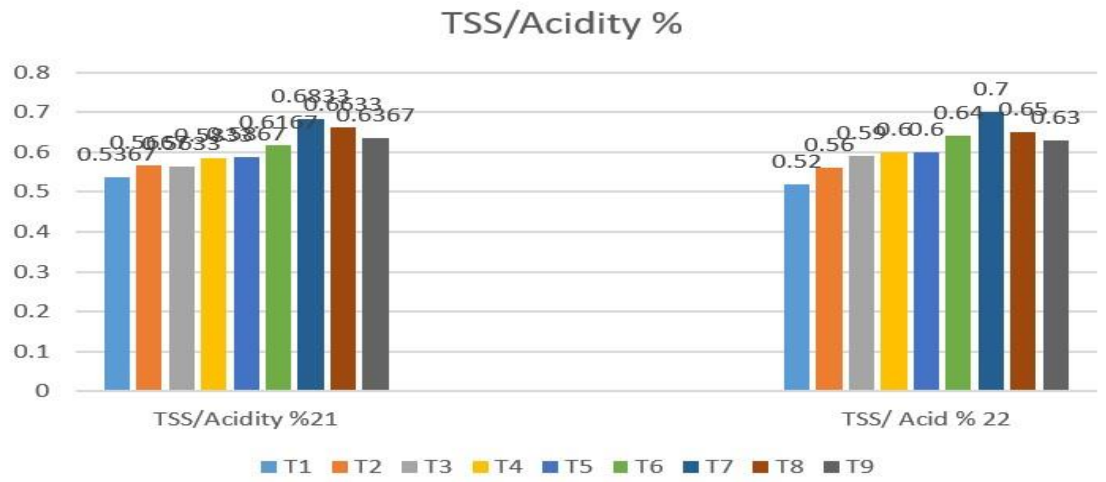


Figure (2): Effect of various treatments on TSS/Acidity ratio of lime fruits

*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

The treatments carried out significantly affected the fruit density of acid lime, particularly T8 which recorded the highest values (1.433 & 1.431), as shown in Figure (3).

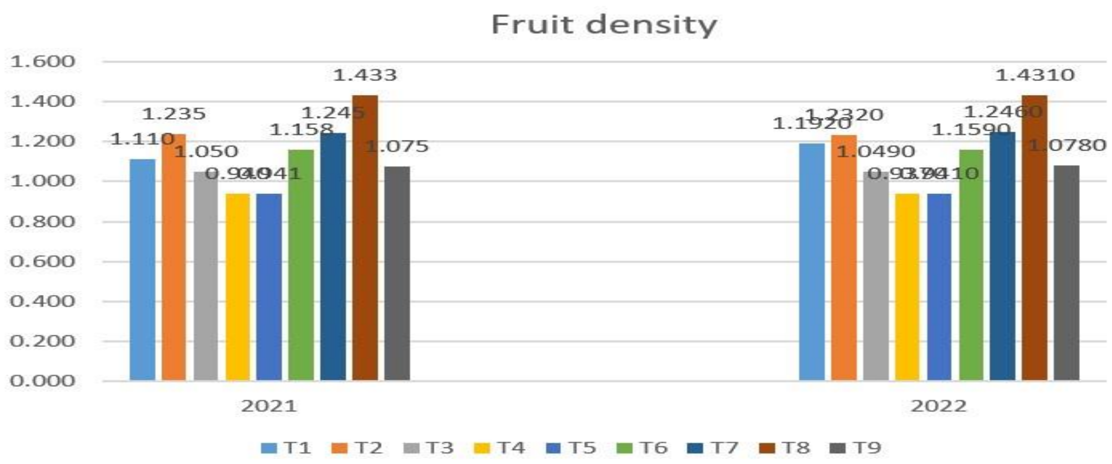


Figure (3): Effect of various treatments on fruit density of lime trees
*T1 (Control), T2 (Si-NPs1), T3 (Si-NPs2), T4 (SE1), T5 (SE2), T6 (Si-NPs 1+SE1), T7 (Si-NPs 1+SE2), T8 (Si-NPs 2+SE1), T9 (Si-NPs 2+SE2).

This study provides more robust results than previously carried out since our research predicted that the combinations of nano-silicon and seaweed extracts exhibited positive responses in the growth and fruiting of the acid lime trees.

The beneficial effects of silicon and nano-silicon on plant growth may be due to enhancing photosynthesis activity, increasing potassium content, activating certain enzymes, and increasing soluble substances in the plant cell (Kumaraswamy, *et al.*, 2021; Meena, *et al*., 2014).

Treatments of Si-NPs and SE increased canopy spread and increased nitrogen and manganese levels. A similar effect on canopy spread was found by (Abo El-Enien, *et al*., 2019) who reported a significant effect of foliar application of Si-NPs on the vegetative growth of Navel orange trees. Likewise, Anli, *et al.*, (2020) claimed that seaweed extract treatment improved growth, increased nitrogen and phosphorus levels, and increased the yield of date palms. Similarly, Hameedawi, *et al*., (2017) on Fig trees & Al-Rawi, *et al.*, (2016) on peach trees reported that seaweed extract treatment enhanced vegetative characteristics and leaf mineral content of peach trees cv. Peento.

The positive effect of the combination of a low rate of applied substances could be due to enhancing dry matter formation and, consequently, increased fruit weight and tree yield. Furthermore, the macro-and micronutrient concentrations in the leaves increased with the application of Si-NPs and SE, indicating improvements in the nutrient status of the tree. The current study explores the essential role of Si-NPs and SE in promoting the growth of immature lime trees to accelerate flowering and production stages. Si-NPs treatments on leaves greatly improve the absorption of Fe and Zn by plant cells and tissues and increase the leaf content of lime trees.

Our findings are in agreement with those of [Ali, *et al.*, 2021; El-Dengawy, *et al*., 2021; El-Sheri, *et al.*, 2020; Al-juthery, 2018; Asgharipour and Mosapor, 2016; Amro, 2015] who reported that using nanoparticles and seaweed extract has many beneficial effects for plants, as it improves vegetative growth, enhances the efficiency of photosynthesis, reduces transpiration, increases dry matter formation, consequently, improves the productivity of trees and total yield.

Foliar application of SE affects fruit quality parameters positively, our results are in agreement with Rana, *et al.,* (2023) on Kiwifruit, who reported that seaweed extract improves fruit quality parameters.

The obtained results of nano-Silicon go in line with the findings of Hassan, *et al.,* (2022) on olive trees and Abo El-Enien *et al.,* (2019) on navel orange trees, who reported that Si-NPs have a positive effect on the yield per trees.

The results of the present investigation showed that the combinations of Si-NPs and SE improved the tree yield over control, total yield, and fruit quality of acid lime trees. The increment in yield may be attributed to the fact that the exogenous application of Si-NPs and SE might increase the formation of dry matter that is supplied to the fruits (Hassan, *et al.,* 2022). Previous studies reported the stimulating effect of seaweed extract on many horticultural crops, which improved plant growth, increased flowering, and increased fruit set, thus increasing tree productivity (Hassan et al., 2021; Anli *et al.,* 2020).

The enhancement in fruit characters by the combinations of Si-NPs and SE applications may be attributed to the fact that increased availability of nutrients and increased cytokinin levels in fruit occur particularly during the cell elongation stage (Abobatta, 2023; Harhash, *et al.*, 2023; Cameron, *et al.*, 2022). Our findings are in the same line as those demonstrated by Rana, *et al*., (2023) on Kiwi fruits, Erogul, *et al*., (2022) on almonds; Ayoub, *et al.,* (2019) on apple trees; Omar, *et al.,* (2017) on palm trees; & Amro, (2015) on Valencia orange, who reported that application of seaweed extract enhances fruit quality.

CONCLUSIONS

Combination of Si-NPs and seaweed extract supply is imperative to immature acid lime trees due to their role in enhancing vegetative growth, fruit set, and minimizing pre-harvest drop, thereby leading to greater yield. Si-NPs and seaweed help in obtaining a better yield. Though these stimulants have different roles within a plant, their combined application can enhance production more than that of individual sprays. Among the treatments, Si-NPs (1 mg/L) and SE (4 cm/L) were the best since they resulted in greater plant canopy spread and total yield and significantly enhanced fruit quality. Hence, it is recommended to spray a combination of Si-NPs and SE to enhance the growth of immature lime trees and fruit yield by improving the fruit quality and reducing the pre-harvest drop of fruit, which, in turn, will help to obtain a greater yield.

ACKNOWLEDGMENT

The researchers thank the Horticulture Research Institute /Agriculture Research Center for providing the given requirements for the research study.

CONFLICT OF INTEREST

The researcher supports the idea that this work does not conflict with the interests of others.

تأثير معاملات السيليكون النانوي ومستخلص الطحالب البحرية في نمو وإثمار أشجار الليمون الصغيرة (*Citrus aurantifolia* Swingle) تحت ظروف التربة الرملية

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الخلاصة

أجري البحث خلال موسمي 2021 و2022 على أشجار الليمون الحامض (*Citrus aurantifolia* Swingle) عمر 3 سنوات مطعومة على أصل ليمون فولكا ماريانا ومنزرعة في تربة رملية تحت نظام الري بالتنقيط في منطقة النوبارية بمحافظة البحيرة. مصر. تهدف الدراسة إلى دراسة تأثير الرش الورقي بثلاثة تركيزات من مستخلص الطحالب البحرية (0، 2، 4 مل. لتر$^{-1}$) والسيليكون النانوي (0، 1، 1.5 مل. لتر$^{-1}$)، على على نمو وإنتاجية أشجار الليمون التى رتبت في قطاعات كاملة العشوائية بثلاثة مكررات لكل معاملة، ومثلت كل مكررة بشجرة واحدة. أظهرت النتائج أن الرش الورقي لمستخلص الأعشاب البحرية مع السيليكون النانوي عززت نمو الاشجار، والمحتوى المعدني للأوراق، وعدد الثمار لكل شجرة، والإنتاج الكلى، وجودة الثمار. أثبتت معاملة السيليكون النانوي (1 مل) مع مستخلص الأعشاب البحرية (4 مل) أنها الأكثر فعالية في تحسين جميع مؤشرات النمو المدروسة خلال التجربة، كما حققت أكبر إنتاجية بنسبة 23.09 و15.31٪ عن الكنترول، وذلك بسبب زيادة عدد الثمار ووزن الثمار. في الختام، أظهرت النتائج المذكورة أعلاه أن التطبيق الورقي للسيليكون النانوي مع مستخلص الأعشاب البحرية يمكن أن يكون له تأثيرات مفيدة على نمو وإنتاجية الأشجار وتحسين جودة ثمار أشجار الليمون غير الناضجة.

الكلمات المفتاحية: الليمون الحامض، السيلكون النانوى، مستخلصات الطحالب، المحصول، جودة الثمار.

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