Journal of Sohag Agriscience (JSAS) 2025, 10(2): 32-43

ISSN 2735-5578
https://jsasj.journals.ekb.eg
JSAS 2025; 10(2): 32-43

Received: 10 -07-2025
Accepted: 22 -07-2025

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Effect of Foliar Application of Nano-Fertilizers and Several Irrigation Levels on Growth and Productivity of Egyption Lime under Environmental Stress Conditions.

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Abstract

The study was conducted at El-Kwamel farm, college of Agriculture, Sohag University, Egypt during three seasons (2021,2022 and 2023) to evaluating the effects of the interaction of foliar application of NPK in Nano-form at different doses of potassium (k) on Egyptian lime trees with applying different irrigation levels to find out the optimum level of irrigation, to enhance vegetative growth and productivity under environmental stress conditions. Thirty six uniform trees of Egyptian lime were sprayed as foliar application twice in the morning when the leaf stomata are open with Nano - NPK included three rates of potassium (k) i.e. (20:20:20), (20:20:40) and (20:20:60) at 2500 ppm were applied prior to flowering start and after one month from fruit set besides 3 trees as a control with three levels of irrigation water: 50, 75 and 100% of Field Capacity (FC). Based on the results, this study recommends the foliar application of Nano-NPK (20:20:40) at 2500 ppm twice—once before flowering and once one month after fruit set—combined with irrigation at 100% of field capacity (FC) as an effective practice for Egyptian lime growers to improve vegetative growth, yield, and fruit quality.

Key words: Egyptian lime, Nano –NPK, irrigation levels, field

INTRODUCTION

In Egypt, citrus crops receive significant attention and are extensively cultivated due to their high nutritional value and importance for local consumption. Economically, citrus represents a vital export commodity, serving as a major source of foreign currency through exports to numerous countries, particularly in Europe and Asia. Additionally, citrus ranks first among all fruit crops in Egypt in terms of production volume and holds the second position globally after grapes in total fruit production. The most widely cultivated citrus species in Egypt include mandarin (Citrus reticulata), sweet orange (Citrus sinensis), and Egyptian lime (Citrus aurantifolia L.). Among these, Egyptian lime is particularly prominent due to its high productivity, year-round availability for fresh consumption, distinctive aromatic flavor, and increasing fruit quality, making it one of the most important citrus fruits in the country. Improving citrus groves productivity in Egypt depended on the use of appropriate management practice including balanced nutrition, proper irrigation technique for each region and integrated pest management (Abobatta, 2018). The application of nano-fertilizers containing essential macronutrients—nitrogen (N), phosphorus (P), and potassium (K)—has demonstrated significant effectiveness in enhancing the vegetative growth, pollination, and floral fertility of fruit trees. This, in turn, leads to increased yield, elevated chlorophyll and protein content, and improved fruit quality, particularly under abiotic stress conditions (Shareef, 2011a; Malerba and Cerana, 2016; Roshdy and Refaai, 2016; Zagzog et al., 2017; Saied, 2018; Zahedi et al., 2019; Al-Hchami and Alrawi, 2020; El-Ramady et al., 2021; Neme et al., 2021; Shilp et al., 2022). Irrigation have great effects on fruit quality in this respect Kallsen, *et al.* (2011) reported irrigation influence on fruit size, quality, total yield, and time of harvest. Besides, Water stress can affect yield and fruit quality. Water deficits have increased the concentration of juice and TSS, especially sugars, through short-term fruit dehydration or longer-term osmotic adjustment (Perez-Perez, *et al.* 2009). Efficient utilization of potassium fertilizers and optimized water management are key factors in maximizing yield and fruit quality in citrus orchards. This study was done to evaluating the effects of the interaction of foliar application of NPK in Nano-form at different doses of potassium (k) and applying different irrigation levels to find out the optimum level of irrigation on Egyptian lime trees, to enhance vegetative growth and productivity under environmental stress conditions.

MATERIALS AND METHODS

Plant material:

This study was carried out during three successive seasons 2021, 2022 and 2023 on 5-years old Egyptian lime trees budded on Volkamer lemon (*Citrus volkameriana* L.) rootstock, which is one of the most important species of citrus in Egypt, grown in sandy soil and spaced 5x5 m apart under drip irrigation system in a citrus orchard located in El-Kwamel farm, college of Agriculture, Sohag University, Egypt, is subject to mild winters and warm and dry summer. All the chosen trees were uniform in growth, free from insects damage and diseases, and were subjected to the same management and cultural practices.

Physical and chemical properties of soil:

Table (1): Some physical and chemical properties of El-Kwamel farm soil at start of the experiment according to the methods described by Page *et al.* (1982) and Klute (1986).

Physical properties	Sand	Silt	Clay	CaCo3%	O.M%	Texture
	89.60	5.85	4.55	3.10	0.07	Sandy
Chemical composition	pH	EC dSm-1	N%	P ppm	K ppm	SO4 meq/L
	8.70	1.20	0.05	0.80	185.0	3.90
	Na meq/L	K meq/L	Ca meq/L	Mg meq/L	Cl meq/L	Hco3 meq/L
	0.54	0.37	8.62	3.28	6.00	3.00

Chemical analyses of irrigation water:

Table (2): Chemical analyses of irrigation water were performed according to the methods described by Ayers and Westcot (1994).

property	unit	value
pH	-	7.64
EC	Mg/-1	971.2
Na	Mg/-1	82.90
K	Mg/-1	134.92
Ca	Mg/-1	80.42
Mg	Mg/-1	40.62
HCO3	Mg/-1	191.06
Cl	Mg/-1	80.26
SO4	Mg/-1	354.72

Climatic data:

Mean monthly temperature and relative humidity (maximum and minimum) for El-Kwamel region (farm location) during 2021, 2022 and 2023 seasons (according to Metrology Organization in Cairo) are shown in Table (3).

Table (3): Meteorological data (mean monthly maximum and minimum temperature and relative humidity) for 2021, 2022 and 2023 under Sohag climatic conditions.*

Month	Temperature (°C)						Humidity (%)					
	2021		2022		2023		2021		2022		2023	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Jan.	7.06	20.94	4.94	16.71	6.13	22.36	38.42	83.26	38.20	79.29	27.29	83.45
Feb.	7.14	21.50	6.86	19.86	7.25	23.57	38.71	81.96	33.17	73.35	19.57	77.82
Mar.	10.94	26.58	8.68	22.48	12.03	27.48	26.23	67.94	22.64	63.35	15.89	68.48
April	15.13	32.03	16.73	34.10	17.07	34.73	19.10	57.97	13.30	50.30	9.23	60.97
May	21.42	37.74	19.10	34.52	19.93	35.90	17.81	48.26	14.38	44.64	9.58	51.61
June	22.80	36.83	22.20	37.20	24.43	40.40	17.90	47.60	16.60	47.10	9.60	50.63
July	25.13	38.90	23.10	37.45	23.84	37.60	17.84	45.32	18.80	49.22	16.29	62.32
Aug.	24.84	39.26	23.84	37.55	23.84	36.97	16.13	47.23	19.96	56.38	15.19	60.26
Sept.	21.93	35.17	22.03	36.40	21.43	34.80	24.27	62.03	21.33	58.80	19.07	69.00
Oct.	17.58	32.35	18.07	30.00	17.61	32.52	24.42	69.39	32.00	71.53	20.93	81.52
Nov.	13.87	28.33	12.73	25.50	14.32	26.10	30.63	74.57	33.53	74.43	25.21	85.58
Dec.	8.00	20.06	10.20	22.5	9.70	23.60	36.10	78.03	37.50	79.66	35.50	89.50

*The meteorological data obtained by Meteorology Organization in Cairo.

Experimental work:

To improve the vegetative growth and productivity of Egyptian lime trees, a total of thirty-six uniform trees were selected and subjected to foliar applications of Nano-NPK fertilizers containing three different potassium (K) levels: 20:20:20, 20:20:40, and 20:20:60, each at a concentration of 2500 ppm. Spraying was carried out twice in the morning, when leaf stomata are most receptive—once before flowering initiation (first week of February) and again one month after fruit set (first week of May). An additional group of three trees was maintained as untreated controls. These treatments were combined with three different irrigation regimes corresponding to 50%, 75%, and 100% of field capacity (FC), calculated using a tensiometer, under the environmental conditions of southern Egypt. Spraying was performed using a 20-liter backpack sprayer until run-off, except for the control trees. A wetting agent (Tween 20 at 1%) was added to the spray solution to lower surface tension and improve droplet adhesion and spread ability. The experiment was carried out over three consecutive seasons.

Treatments:

The details of the treatment composition were as follow: T1. Control (untreated), T2. Nano NPK (20:20:20) 2500 ppm with irrigation at 50, 75 and 100 % of FA, T3. Nano NPK (20:20:40) 2500 ppm with irrigation at 50, 75 and 100 % of FA and T4. Nano NPK (20:20:60) 2500 ppm with irrigation at 50, 75 and 100 % of FA.

Experimental design:

This experiment was arranged in Randomized Complete Block Design (RCBD) with three replications (one three pear each replicate), in split plot method with three irrigation levels in main plots, and Nano- NPK included three rates of potassium (k) in sub plots during 2021,2022 and 2023 seasons.

Data were recorded for the following parameters:

Vegetative growth:

Number of leaves per shoot: Twelve shoots (one year-old sprout) were randomly selected around each tree canopy (replicate) to record the number of leaves per shoot. Leaf area (cm^2): In each study season, samples of approximately 30 leaves per. Tree were taken from the mid shoot growth (one year-old sprout) from the most representative shoot of the four sides of the tree to determine average leaf surface area ($cm.^2$) according to the equation described by (Mofeed, 2009).

Leaf area (cm^2) = 0.41 (leaf length x leaf width) + 1.83

Leaf total chlorophyll content (SPAD).

Leaf chlorophyll concentration (SPAD values) was estimated with a chlorophyll meter (SPAD – 502 - plus, Japan).

Productivity:

Fruit set, drop and retention percentage: Ten shoots one-year-old per each-tree (replicate) were selected and tagged at random, total number of flowers per shoot was counted at full bloom and fruit set was counted two week after full bloom stage. The number of dropped fruits were counted after one month from set and calculated as percentages based on set fruits. The average number of fruits per shoot were recorded at the time of harvesting. Percent fruit set (FS %), fruit drop (FD %) and fruit retention (FR %) was calculated by the following formula:

$$\text{FS (\%)} = \frac{\text{Number of fruitlets/shoot at time of set}}{\text{Number of flowers/shoot at full bloom}} \times 100$$

$$\text{FD (\%)} = \frac{\text{Number of fruit set} - \text{number of fruit retention}}{\text{Number of fruit set}} \times 100$$

$$\text{FR (\%)} = \frac{\text{Number of fruits at harvesting time}}{\text{Number of fruitlets at time of set}} \times 100$$

Fruit yield (Kg/tree):

Fruits from all treated Egyptian lime trees were harvested during the period from 15th July to the last week of August in each of the 2021, 2022, and 2023 seasons, corresponding to the typical harvest period for the region. At harvest, the total number of fruits per tree was counted, and the total fruit weight was recorded to determine the yield per tree (kg).

Fruit quality:

Fruit physiochemical characteristics upon harvest: At harvest time, ten fruits from each selected tree (replicate) were chosen randomly to determine the following physic-chemical traits which included fruit weight determined by weighting 10 fruits and the average were recorded in (g) and fruit juice volume (ml) was calculated. The chemical properties were determined by using standard procedures. Total soluble solids percentage (TSS%) was estimated in fruit juice using a hand refractometer (A.O.A.C., 1995), total acidity (as g citric acid)/100 ml juice) was determined by titrating the known volume of juice with 0.1 N NaOH, using phenolphthalein as an indicator (A.O.A.C., 1995) and Ascorbic acid (V.C mg /100g juice) content was measured by titration against 2, 6-dichlorophenolindo phenol was also estimated by the method described in A.O.A.C (1995).

Statistical analysis:

Factorial experiment data were subjected to analysis of variance according to Snedecor and Cochran (1980). Means were compared by the least significant difference test (L.S.D) at 0.05 level of probability; the small

letters were used for differentiating the values of interaction effects of investigated factors.

RESULT AND DISCUSSION

This study was conducted to evaluate the interactive effects of foliar application of commercial Nano-NPK fertilizers with varying potassium (K) concentrations, applied twice (prior to flowering and post-fruit set), in combination with different irrigation regimes on Egyptian lime trees. The investigation focused on assessing selected vegetative growth traits and productivity indicators under environmental stress conditions across the 2021, 2022, and 2023 growing seasons.

Effect on growth:

The data present in tables (4, 5 and 6) show leaves number per shoot, leaf area (cm^2) and leaf total chlorophyll content (SPAD) as affected by the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation during 2021, 2022 and 2023 growing seasons of Egyptian lime trees.

Table (4): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on leaves number per shoot of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levelss / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	33.00^{d}	51.66^{c}	51.00^{c}	42.66^{f}	43.66^{f}	58.00^{cd}	55.00^{ef}	58.33^{d}	66.00^{bc}
Nano-NPK(20:20:20) 2500 ppm	50.33^{c}	48.00^{c}	59.66^{ab}	51.33^{e}	54.33^{de}	69.00^{ab}	64.66^{c}	54.00^{f}	55.33^{ef}
Nano-NPK(20:20:40) 2500 ppm	47.00^{c}	49.33^{c}	66.00^{a}	64.66^{b}	72.33^{a}	72.00^{a}	68.33^{b}	67.66^{b}	74.00^{a}
Nano-NPK(20:20:60) 2500 ppm	58.66^{b}	51.66^{c}	48.33^{c}	59.66^{c}	66.33^{b}	72.66^{a}	56.66^{de}	64.66^{c}	67.66^{b}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyption lime trees according to L.S.D. at 0.05 levels.

As related to number of leaves per shoot, statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in each of the three seasons. The highest values achieved by Nano-NPK(20:20:40) treatment at 2500 ppm x irrigation level at 100% (66.00, 72.00 and 74.00), respectively in each of the three seasons compared to the control and other treatments except in the second season there were insignificant differences between Nano-NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100%, Nano-NPK (20:20:40) treatment at 2500 ppm x irrigation level at 75% and Nano-NPK (20:20:60) treatment at 2500 ppm x irrigation levels at 100% .

Table (5): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on leaf area (cm^2) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	10.17b	12.91^{ab}	12.12^{ab}	11.28^{c}	14.02^{abc}	13.72^{abc}	12.03^{d}	14.77^{abc}	14.00^{bcd}
Nano-NPK (20:20:20) 2500 ppm	12.40^{ab}	12.25^{ab}	13.92^{ab}	13.97^{abc}	13.37^{ab}c	14.65^{abc}	16.12^{ab}	14.08^{bcd}	15.31^{abc}
Nano-NPK (20:20:40) 2500 ppm	12.57^{ab}	11.68^{ab}	15.72^{a}	13.53^{abc}	12.69^{bc}	16.58^{a}	13.92^{bcd}	13.32^{cd}	17.26^{a}
Nano-NPK(20:20:60) 2500 ppm	15.09^{ab}	12.19^{ab}	11.05^{ab}	15.47^{ab}	14.07^{abc}	12.48^{bc}	16.39^{ab}	16.03^{ab}	14.57^{bcd}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In terms of leaf area (cm^2), statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in each of the three seasons. The highest values achieved by Nano-NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% (15.72, 16.58 and 17.26cm^2), respectively in each of the three seasons compared to the control and other treatments.

Table (6): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on leaf total chlorophyll content (SPAD) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	26.73^{ef}	27.73^{def}	28.73^{de}	21.97^{c}	25.43^{ab}	24.43^{c}	30.43^{g}	31.80^{f}	34.87^{e}
Nano-NPK (20:20:20) 2500 ppm	25.07^{f}	35.07^{c}	29.17^{d}	34.67^{ab}	34.87^{ab}	32.20^{b}	29.47^{h}	30.10^{g}	38.10^{b}
Nano-NPK (20:20:40) 2500 ppm	29.37^{d}	38.97^{b}	43.30^{a}	34.10^{ab}	36.30^{a}	37.33^{a}	37.37^{c}	37.30^{c}	38.83^{a}
Nano-NPK (20:20:60) 2500 ppm	33.80^{c}	34.80^{c}	35.73^{c}	33.93ab	35.87ab	34.97ab	35.70^{d}	37.53^{c}	35.03^{e}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In regard to leaf total chlorophyll content (SPAD), statistical analysis indicated significant differences due to the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in all of the three seasons. The highest values in all of the three seasons were recorded for NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% (43.30, 37.33 and 38.83SPAD), respectively compared with the control and other treatments with insignificant differences between NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% and NPK (20:20:40) treatment at 2500 ppm x irrigation level at 75% in the second season.

Effect on productivity:

The data present in tables (from 7 until 10) show the fruit set (%), fruit retention (%), fruit drop (%) and yield (Kg/ tree) as affected by the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation during 2021, 2022 and 2023 growing seasons of Egyptian lime trees.

Table (7): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on fruit set (%) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	23.93^{k}	26.63^{jk}	29.66^{h}	60.29^{f}	61.54^{e}	61.23^{e}	64.47^{de}	62.14^{fg}	59.35^{g}
Nano-NPK(20:20:20) 2500 ppm	28.30^{i}	55.70^{cd}	46.06^{g}	71.65^{b}	66.21^{d}	60.82^{f}	57.92^{h}	67.22^{bc}	65.42^{c}
Nano-NPK(20:20:40) 2500 ppm	71.55^{b}	60.20^{bc}	83.90^{a}	49.98^{g}	66.19^{d}	80.03^{a}	68.85^{b}	63.28^{e}	70.44^{a}
Nano-NPK(20:20:60) 2500 ppm	48.56f^{g}	50.86^{e}	52.56^{de}	70.89^{cd}	61.78^{e}	78.88^{ab}	68.55^{b}	69.42^{ab}	64.15^{de}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

Concerning the fruit set percentage; statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in each of the three seasons. The highest values achieved by Nano-NPK

(20:20:40) at 2500 ppm treatment x irrigation level at 100% (83.90, 80.03 and 70.44%), respectively in each of the three seasons compared with the control and other treatments.

Table (8): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on fruit retention (%) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	52.86^{bc}	61.10^{bc}	59.63^{bc}	55.53^{dc}	71.43^{bc}	52.86^{e}	78.10^{bcd}	70.54^{de}	68.97^{de}
Nano-NPK (20:20:20) 2500 ppm	53.77^{bc}	72.67^{b}	58.33^{bc}	79.63^{b}	72.43^{bc}	71.10^{bc}	63.66^{e}	84.38^{abc}	74.52^{cd}
Nano-NPK (20:20:40) 2500 ppm	40.16^{c}	70.40^{b}	95.83^{a}	68.48^{bcd}	63.43cde	98.46^{a}	69.40^{de}	63.93^{e}	90.83^{a}
Nano-NPK(20:20:60) 2500 ppm	74.43^{b}	60.11^{bc}	73.10^{b}	77.76^{bc}	79.33^{b}	74.73^{bc}	81.44^{abc}	86.38^{ab}	88.27^{ab}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

As related to the fruit retention percentage, statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in all of the three seasons. The highest value achieved by the Nano-NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% (95.83, 98.46 and 90.83%), respectively in all of the three seasons compared to the control and other treatments.

Table (9): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on fruit drop (%) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	68.27^{a}	45.77^{d}	63.20^{b}	68.27^{a}	32.23^{cd}	38.17^{b}	30.40^{a}	25.73^{b}	19.16^{gh}
Nano-NPK(20:20:20) 2500 ppm	38.03^{f}	38.63^{f}	38.40^{gh}	38.03^{b}	38.40^{b}	38.63^{b}	23.90^{cd}	23.73^{cd}	21.96^{e}
Nano-NPK(20:20:40) 2500 ppm	41.63^{ef}	33.07^{h}	33.90^{hg}	32.77^{cd}	28.03^{e}	13.30^{f}	23.60^{cd}	18.80^{h}	20.13^{fg}
Nano-NPK(20:20:60) 2500 ppm	65.10^{ab}	54.63^{cd}	38.77^{f}	29.27^{de}	35.30^{c}	21.73^{ef}	20.86^{fg}	24.76^{bc}	18.66^{h}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In regard to the fruit drop percentage, statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in each of the three seasons. The lowest values achieved by NPK(20:20:40) treatment at 2500 ppm x irrigation level at 100% (33.90, 13.30 and 20.13%) in each of the three seasons compared to the control and other treatments.

Table (10): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on yield/tree (Kg) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	4.63^{de}	4.90^{bcde}	5.30^{abc}	3.83^{e}	4.80^{d}	5.20^{c}	5.80^{g}	6.00^{ef}	5.83^{eg}
Nano-NPK(20:20:20) 2500 ppm	4.40^{e}	5.33^{ab}	5.10^{a-d}	3.83^{e}	5.43^{c}	5.87^{b}	5.70^{gh}	6.67^{bc}	5.53^{h}
Nano-NPK(20:20:40) 2500 ppm	4.53^{e}	5.10^{abcd}	5.43a	4.70d	5.43c	6.60^{a}	6.07e	6.80b	7.00a
Nano-NPK(20:20:60) 2500 ppm	4.80^{cde}	4.87^{bcde}	5.30^{abc}	4.90^{d}	3.97^{e}	6.40^{a}	6.50^{cd}	6.40^{d}	5,10^{i}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

With respect to yield/tree ((Kg), statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in all of the three seasons. The highest values achieved by NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% (5.43, 6.60 and 7.00 Kg), respectively in all of the three seasons with insignificant differences between NPK(20:20:40) at 2500ppm x irrigation level at 100% and NPK(20:20:60) treatment at 2500 ppm x irrigation level at 100% in the second season compared to the control and other treatments.

Effect on some fruit physical characters:

The data present in tables (11and 12) show the fruit weight (g) and fruit juice volume (g) as affected by the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation during 2021, 2022 and 2023 growing seasons of Egyptian lime trees.

Table (11): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on fruit weight (g) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	4.40^{e}	5.33^{ab}	5.10^{a-d}	3.83^{e}	4.80^{d}	5.20^{c}	5.80^{g}	6.00^{ef}	5.83^{eg}
Nano-NPK(20:20:20) 2500 ppm	4.63^{de}	4.90 $^{b-e}$	5.30^{abc}	3.83^{e}	5.43^{c}	5.87^{b}	5.70^{gh}	6.67^{bc}	5.53^{h}
Nano-NPK(20:20:40) 2500 ppm	4.53^{e}	5.10 $^{a-d}$	5.43^{a}	4.70^{d}	5.43^{c}	6.60^{a}	6.07^{e}	6.80^{b}	7.00^{a}
Nano-NPK(20:20:60) 2500 ppm	4.80^{cde}	4.87 $^{b-e}$	5.30^{abc}	4.90^{d}	3.97^{e}	6.40^{a}	6.50c^{d}	6.40^{d}	5,10^{i}
Mean	4.59^{B}	5.05^{A}	5.28^{A}	4.32^{C}	4.91^{B}	6.02^{A}	6.02a^{B}	6.47^{A}	5.87^{B}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

As for the fruit weight (g), statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments in each of the three seasons. The highest values achieved by NPK (20:20:40) treatment at 2500 ppm x irrigation level at 100% (5.43, 6.60 and 7.00g), respectively in each of the three seasons with insignificant differences between Nano-NPK (20:20:40) and Nano-NPK (20:20:60) at 2500 ppm treatments x irrigation level at 100% in the second season compared to the control and other treatments.

Table (12): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on fruit juice volume (ml) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	1.32^{h}	1.98^{f}	2.03^{ef}	3.09^{c}	2.55^{e}	3.27^{bc}	4.0.6^{f}	4.25^{ef}	4.32^{e}
Nano-NPK(20:20:20) 2500 ppm	1.27^{gh}	2.45^{d}	1.72^{fg}	2.60^{e}	3.87^{ab}	2.79^{cd}	4.88^{cd}	4.89^{c}	4.92^{bc}
Nano-NPK(20:20:40) 2500 ppm	2.95^{bc}	3.11^{b}	3.76^{a}	3.23^{bc}	2.69^{d}	4.37^{a}	4.64^{d}	5.05^{b}	5.27^{a}
Nano-NPK(20:20:60) 2500 ppm	2.77^{c}	1.48^{g}	3.51^{ab}	3.15b^{c}	3.15b^{c}	3.18b^{c}	5.19^{ab}	5.21^{a}	4.99^{bc}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In terms of fruit juice volume (ml), statistical analysis indicated significant differences for the interaction of different irrigation levels and Nano-fertilizers (NPK) treatments. The highest values achieved by NPK(20:20:40) treatment at 2500 ppm x irrigation levels at 100% (3.76, 4.37 and 5.27 ml), respectively in each of the three seasons compared to the control and other treatments.

Effect on some fruit chemical characters:

The data present in tables (from 13, 14 and 15) show the total soluble solids percentage (TSS %), total acidity (%) and ascorbic acid (VC) content (mg/100g juice) as affected by the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation during 2021, 2022 and 2023 growing seasons of Egyptian lime trees.

Table (13): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on total soluble solids (%) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	6.67^{e}	6.00^{g}	8.33^{c}	8.33^{cd}	9.00^{bc}	8.33^{cd}	7.67^{c}	8.33^{b}	8.00^{bc}
Nano-NPK(20:20:20) 2500 ppm	7.00^{d}	8.33^{c}	8.67^{bc}	8.33^{cd}	9.33^{ab}	9.33^{ab}	7.33c^{d}	7.00^{d}	9.00^{a}
Nano-NPK(20:20:40) 2500 ppm	9.33^{ab}	7.67^{cd}	9.67^{a}	7.67^{d}	9.00^{bc}	10.00^{a}	9.00^{a}	8.67^{ab}	9.00^{a}
Nano-NPK(20:20:60) 2500 ppm	6.33^{f}	9.33^{ab}	9.00^{b}	9.00^{bc}	8.67^{c}	9.33^{ab}	8.00^{bc}	9.00^{a}	8.00^{bc}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyption lime trees according to L.S.D. at 0.05 level.

Concerning the total soluble solids (TSS) percentage, Statistical analysis indicated significant differences for the interaction of different irrigation regimes and Nano-fertilizers (NPK) treatments in all of the three seasons. The highest values in all of the three seasons were always recorded for NPK(20:20:40) at 2500 ppm x irrigation regime at 100% (9.67, 10.00 and 9.00%), respectively with insignificant differences between NPK(20:20:40) at 2500 ppm x irrigation regime at 100% and NPK(20:20:20) at 2500 ppm x irrigation regime at 100% as well as between NPK(20:20:40) at 2500 ppm x irrigation regime at 100% and NPK(20:20:60) at 2500 ppm x irrigation regime at 75% in the third season compared to the control and other treatments.

Table (14): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on total acidity (%) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	6.80^{de}	8.77^{ab}	7.57^{c}	7.27^{ef}	7.98^{cd}	6.53^{f}	6.42^{ef}	6.43^{ef}	9.53^{b}
Nano-NPK(20:20:20) 2500 ppm	7.00^{d}	8.73^{b}	6.13^{g}	6.03^{h}	8.77^{b}	7.33^{d}	9.10^{bc}	9.57^{b}	5.23^{g}
Nano-NPK(20:20:40) 2500 ppm	7.03^{d}	6.37^{f}	9.88^{a}	8.53^{bc}	6.40^{g}	10.00^{a}	7.40^{d}	8.63^{cb}	10.67^{a}
Nano-NPK(20:20:60) 2500 ppm	6.53^{e}	8.33^{bc}	7.23^{cd}	7.10^{fg}	8.00^{c}	9.43^{ab}	8.93^{c}	9.97^{ab}	7.01^{e}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In regard to acidity percentage, Statistical analysis indicated significant differences for the interaction of different irrigation regimes and Nano-fertilizers (NPK) treatments. The highest values achieved by NPK(20:20:40) treatment at 2500 ppm x irrigation regime at 100% (9.88, 10.00 and 10.67%), respectively in each of the three seasons compared to the control and other treatments.

Table (15): Mean values of the interaction of Nano-fertilizers (NPK) treatments and different levels of irrigation on ascorbic acid content (mg/100g juice) of Egyptian lime trees during 2021, 2022 and 2023 seasons.

Irrigation levels / Nano-NPK treatments	Season 2021			Season 2022			Season 2023		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Control	32.97^{d}	28.77^{e}	32.97^{d}	50.73^{c}	49.47^{cd}	45.23^{d}	57.60^{cd}	57.37^{cd}	57.43^{cd}
Nano-NPK(20:20:20) 2500 ppm	31.13^{de}	37.10^{ab}	34.43^{c}	50.14^{c}	53.67^{abc}	43.63^{f}	58.70^{ab}	56.73^{d}	57.40^{cd}
Nano-NPK(20:20:40) 2500 ppm	32.70^{cd}	37.13^{ab}	40.83^{a}	54.70^{ab}	51.67^{bc}	57.40^{a}	58.17^{bc}	59.20^{a}	59.20^{a}
Nano-NPK(20:20:60) 2500 ppm	33.10^{cd}	37.00^{ab}	34.63^{c}	44.50^{ef}	50.50^{c}	57.78^{a}	55.70^{e}	58.57^{ab}	59.40^{a}

Mean separation within the interaction between NPK treatments and irrigation regimes of the Egyptian lime trees according to L.S.D. at 0.05 level.

In terms of ascorbic acid content (mg/100g juice), Statistical analysis indicated significant differences for the interaction of different irrigation regimes and Nano-fertilizers (NPK) treatments in all of the three seasons. The highest values achieved by NPK(20:20:40) treatment at 2500 ppm x irrigation regime at 100% (40.83, 57.40and 59.20 mg/100g juice), respectively in all of the three seasons with insignificant differences between NPK(20:20:40) at 2500 ppm x irrigation regime at 100% and NPK(20:20:60) at 2500 ppm x irrigation regime at 100% in the second and third second as well as between NPK(20:20:40) at 2500 ppm x irrigation regime at 100% and NPK(20:20:40) at 2500 ppm x irrigation regime at 75% in the third season compared to the control and most treatments. The study results were in agreement with those obtained by Goramnagar, *et al.* (2020) who who revealed that evident that, flowers borne on one meter shoot had shown statistical difference due to an irrigation and fertigation levels. Fruit set and fruit retention data was non-significant due to the irrigation levels. However, the higher fertigation level produced significantly the maximum fruit set and fruit retention. Also, Atawia *et al.* (2021) indicated that, Nano

fertilizer treatments as foliar spray at various concentrations and irrigation with high level resulted in a positive and significant increase in most vegetative growth measurements.

CONCLUSION

The results demonstrated that the application of Nano-NPK fertilizer at a ratio of (20:20:40) with a concentration of 2500 ppm combined with irrigation at 100% of field capacity was the most effective in:

- Enhancing vegetative growth (leaf number, leaf area, chlorophyll content),
- Increasing productivity (fruit set percentage, fruit retention, yield per tree) while reducing fruit drop,
- Improving physical fruit characteristics (fruit weight, juice volume),
- And enhancing fruit quality chemically (TSS, acidity, and vitamin C content).

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