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Improves Superior Grapevines Performance Using Nano-fertilizers Compared to Traditional Methods

Ali Hassan Ali* and Reda Hussin Ibrahem

Hort. Dept. Fac. of Agric. Minia Univ., Egypt.

https://doi.org/10.37229/fsa.fjas.2025.11.05

***Corresponding author:** ali.sayed1@mu.edu.eg

Future Science Association

Available online free at www.futurejournals.org

Print ISSN: 2767-178X

Online ISSN: 2767-181X

Received: 5 September 2025
Accepted: 25 October 2025
Published: 5 November 2025

Abstract: This study investigated the effects of foliar-applied nano- and traditional fertilizers of macro- and micronutrients on the vegetative growth and chemical composition of Superior grapevines over two seasons of 2023 and 2024. Thirteen treatments which was conducted using a Randomized Complete Block Design (RCBD) with 3 replicates, including nano-formulations of N, P, K, Fe, Zn, and Mn, were compared with traditional fertilization and control. Nano-fertilization significantly enhanced shoot length, leaf number, leaf area, pruning wood weight, and cane thickness, with nano-nitrogen (10 g N/vine/year) and nano-iron (5 ppm/vine / year) showing the most pronounced improvements in vegetative parameters and chlorophyll content. Nano-fertilizers promoted higher nutrient use efficiency, and resulted in greater nutrient accumulation in grapevine leaves compared to traditional methods. The findings support integrating nano-fertilization in viticulture for efficient nutrient use, improved plant performance, and enhanced fruit quality, recommending foliar nano-N and nano-Fe application for superior vegetative and reproductive traits in Superior grapevines under the same condition.

Key words: Macro-, micro-nutrients, nano-fertilizers, vegetative, chemical content and Superior grapevines.

1. Introduction

Superior grapevines are of significant importance in Egypt, serving as one of the premier early seedless table grape varieties highly adapted to Egyptian climates and consumer preferences. Their cultivation stretches from the Nile Delta to reclaimed desert lands, supporting Egypt's rank as the third-largest global producer of table grapes (**Mostafa *et al.*, 2023**). Egypt's grape cultivation covers a total area of 186735 feddans, with 175245 feddans actively productive and yielding an annual output of approximately 1715410 tons. In the Minia Governorate, grape farming extends across 21098 feddans, of which 20852 feddans are currently productive, generating about 205244 tons of grapes annually according to Ministry of Agriculture and Land Reclamation data (**MALR, 2023**). Superior grapevines cultivar is essential for both export and local consumption, valued for their desirable fruit quality, early maturation, and contribution to increased annual exports, especially in European markets (**Aziz *et al.*, 2022**).

It has become more difficult for the global agriculture industry to increase crop output while fostering environmental sustainability in recent years. Despite their effectiveness, conventional fertilizers frequently cause large nutrient losses through fixation, volatilization, and leaching. These losses lead to environmental problems and a reduction in nutrient utilization (**Kekeli *et al.*, 2025**). The use of these fertilizers significantly increases the emission of greenhouse gases, especially nitrous oxide (N_2O), which possesses a global warming potential nearly 300 times that of carbon dioxide. The release of ammonia from urea plays a significant role in atmospheric pollution and leads to indirect emissions of nitrous oxide. Furthermore, the overapplication of fertilizers contributes to nutrient runoff and leaching, which in turn causes soil acidification, nutrient imbalance, and heightened soil erosion (**Li *et al.*, 2018; Zhang *et al.*, 2022**). These processes damage the microbial communities that are essential to preserving soil fertility and deteriorate the quality of the soil. Additionally, fertilizer leachate contamination of water bodies results in eutrophication and endangers aquatic ecosystems as well as human health (**Pandian *et al.*, 2024**). Together, these environmental effects jeopardize human health, sustainable agriculture, and soil health, underscoring the pressing need to provide sustainable and environmentally friendly fertilizer substitutes.

One potential remedy for these issues is the use of nano-fertilizers in agriculture. Conventional foliar fertilizers demonstrate reduced efficiency owing to their substantial particle size (> 100 nm), which hinders leaf absorption (**Alzreejawi and Al-Juthery, 2020**). Nano-fertilizers, characterized by ultrafine particles (< 100 nm), present a viable solution for enhancing uptake efficiency and act as a sustainable alternative in contemporary agriculture (**Mohamed *et al.*, 2022; El-Shereif *et al.*, 2023**). These fertilizers boost crop growth and production just as well as, or even better than, traditional NPK, and they work even when applied at lower rates. In certain instances, studies on citrus trees (**El-Shereif *et al.*, 2023**), date palms (**El-Sayed, 2018**), and grapevines (**Mohamed *et al.*, 2022**) have shown that nano NPK improves plant growth, yield, and fruit quality. What's more, this effect is observed even when conventional fertilization is reduced; furthermore, using half the standard dose of nano NPK usually results in no compromise in productivity. The enhancement is primarily due to the nanoscale dimensions of these fertilizers, which promote improved absorption and infiltration into plant tissues. The amalgamation of nano-fertilizers with traditional fertilization methods has yielded encouraging results in several cropping systems. These integrated techniques improve nutrient efficiency while maintaining soil integrity (**Kumar and Dahiya, 2024**). This method facilitates the decrease of traditional fertilizer application rates while sustaining or enhancing crop output (**Vadlamudi *et al.*, 2022**).

This study aims to examine the impact of macro and micro nano-fertilizers applied alone via foliar methods on enhancing vegetative growth, and chemical composition of Superior grapevines, while preserving soil health, in comparison to traditional foliar application methods.

2. Martial and Methods

2.1. Description of the experimental site

This experiment was conducted over two consecutive seasons, 2023 and 2024, involving thirty-nine Superior grapevines cultivated at a private orchard in Dafash village, Samalut Center, Minia Governorate, characterized by clay soil (Table A), analyzed adhering to the methodology established by **Wilde *et al.* (1985**). The chosen vines were approximately 10 years old at the commencement of this study, planted at a spacing of 2 × 3 m, and were exposed to comparable horticultural practices. A surface irrigation system utilizing Nile water was implemented. On 1st January, the selected vines exhibited a total of 84 buds, comprising 6 fruiting spurs with 12 buds each and 6 renewal spurs with 2 buds, following a cane pruning strategy, using Gable supporting system. The experiment included thirteen treatments; each replicated three times.

Table (A). Features of the soil under investigation

Soil characters		2023/2024
Particle size distribution (%)	**Sand**	3.09
	Silt	35.11
	Clay	61.80
	Texture class	Clay
EC ppm (1:2.5 extract)		283
pH (1:2.5 extract)		7.90
Organic matter %		2.09
$CaCO_3$ %		2.65
Soil nutrients	**Total N (%)**	0.19
	Available P (ppm)	5.02
	Available K (ppm)	481.0
	Zn (ppm)	1.82
	Fe (ppm)	2.2
	Mn (ppm)	3.16
	Cu (ppm)	0.09

2.2. Experimental treatments and design

Thirteen treatments were used in the experiment, which was conducted using a Randomized Complete Block Design (RCBD). Each treatment was replicated three times, with one vine per treatment. The present experiment set up to compare the traditional fertilization with nano-fertilization included the following treatments:

1. Control
2. Traditional-N (60 g N/vine/year)
3. Traditional-P (84 g P_2O_5/vine/year)
4. Traditional-K (240 g K_2O/vine/year)
5. Traditional-Fe (100 ppm/vine/year)
6. Traditional-Zn (50 ppm/vine/year)
7. Traditional-Mn (50 ppm/vine/year)
8. Nano-N (N-NPs at 10 g N/vine/year)
9. Nano-P (P-NPs at 14 g P_2O_5/vine/year)
10. Nano-K (K-NPs at 40 g K_2O/vine/year)
11. Nano-Fe (Fe-NPs at 10 ppm/vine/year)
12. Nano-Zn (Zn-NPs at 5 ppm/vine/year)
13. Nano-Mn (Mn-NPs at 5 ppm/vine/year)

Traditional nitrogen, phosphorus, and potassium were applied at rates of 60 g N, 84 g P_2O_5, and 240 g K_2O per vine annually, utilizing the following forms ammonium nitrate (33.5% N), mono calcium superphosphate (15.5% P_2O_5), and potassium sulfate (40% K_2O), respectively. Nitrogen mineral fertilizer was applied in three unequal increments: 40% at the onset of growth, 30% immediately following berry setting, and 30% thirty days thereafter. Traditional potassium fertilizer was applied in two equal doses: the first prior to blooming and the second immediately following berry set. As for the traditional phosphorus fertilizer was applied twice, first in conjunction with farmyard waste and second prior to flowering. Traditional micronutrients in form of EDTA include Fe (100 ppm), Zn (50 ppm), and Mn (50 ppm). The micro-nutrient was sprayed conducted three times till runoff using a hand sprayer at the onset of vegetative development, post fruit set, and one month following the second application. As for, Nano-fertilization, N (10 g N), P (140g P_2O_5) and K (40 g K_2O)/vine/year, while Fe (10 ppm), Zn (5 ppm) and Mn (5 ppm) were added once at growth start.

2.3. Measurements

- Vegetative measurements

At the end of the growth season, four new shoots were randomly selected from each vine for measurement the following parameters: Main shoot length (cm), number of leaves/shoot, cane thickness (cm), pruning wood weight/vine (kg), and leaf area (cm^2): The following equation was utilized to evaluate twenty leaves from each vine, situated opposite the basal clusters as per the findings of **Ahmed and Morsy, (1999**)

$$\text{Leaf area} = 0.56\ (0.79 \times w^2) + 20.01.\ \text{where, W = the maximum leaf width,}$$

- Leaf chemical analysis

Pigments: Utilizing the approach established by **Von Wettstein (1957**), the subsequent leaf pigments were extracted: chlorophyll a, chlorophyll b, total chlorophyll, and total carotenoids (mg/100g FW) from ten leaves positioned opposite the initial basal clusters on the recent shoots, collected during the first week of May.

Nutrients: During the first week of July, an analysis was conducted on the concentrations of nitrogen, phosphorus, and potassium percentages, alongside the levels of zinc, iron, and manganese (ppm) within the leaf petioles associated with the basal clusters, following the methodologies established by **Cottenie *et al.* (1982**) and **Balo *et al.* (1988**).

2.4. Statistical analysis

Consistent with the findings of **Mead *et al.* (1993**), the analysis of all data was conducted employing a new L.S.D. technique at significant of 5%.

3. Results and Discussion

3.1. Features of Vegetative Development

Tables 1, illustrate the impact of foliar applications of traditional and nano-fertilizers of macronutrients (NPK) and micronutrients (Zn, Mn, and Fe) at varying concentrations on several vegetative growth parameters. The parameters assessed comprise main shoot length, leaf number, leaf area, average pruning weight, and cane thickness, evaluated across two successive growing seasons.

Data in Table (1) clearly show that all foliar application treatments under investigation whether traditional or nano-fertilizers significantly improved vegetative growth parameters compared to the control vines. It is evident from the data in same Table that nano NPK outperformed the traditional or comparison treatment in this trait, but the addition of nano N at the level of 10 g N/vine/year gave the highest averages in this characteristic and significantly outperformed all other treatments followed by the addition of other nano treatments. The treatment of nano-N recorded the highest mean values of the parameters over the traditional-N in the two seasons. Comparing to the control treatment, the addition of nano-N increased the main shoot length by (22.87 and 22.53%), leaf number (99.24 & 64.14%), leaf area (28.12 & 27.60%), average pruning weight (9.60 & 11.17%), and cane thickness (34.23 & 34.51%), respectively in 2023 and 2024, respectively. As for the nano-micronutrient, from the same Table, it was found that using nano-Fe was the best as micro-nutrient and recorded highest values after nano-N over the traditional fertilization and control treatment. The same trend was true during two seasons.

Table (1). Impact of traditional and nano-fertilization on Superior grapevines vegetative growth parameters across 2023 and 2024 seasons

Characteristics / Treatments	Main shoots length (cm)		Number of leaves/shoot		Leaf area (cm^2)		Pruning wood weight (kg)/vine		Cane thickness (cm)	
	2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Control	96.6	97.2	13.2	14.5	95.3	96.0	1.77	1.79	1.11	1.13
Traditional-N (60 g N)	109.6	111.0	21.1	21.6	110.1	110.5	1.87	1.90	1.34	1.41
Traditional-P (84 g P_2O_5)	107.7	108.5	17.3	18.8	107.8	109.5	1.78	1.80	1.26	1.30
Traditional-K (240 g K_2O)	105.9	106.6	15.1	15.9	105.9	107.4	1.70	1.75	1.16	1.21
Traditional-Fe (100 ppm)	106.6	107.5	19.0	20.2	109.2	109.5	1.80	1.81	1.27	1.28
Traditional-Zn (50 ppm)	105.4	106.3	16.9	17.7	107.6	108.0	1.71	1.74	1.19	1.23
Traditional-Mn (50 ppm)	104.3	105.2	14.9	15.6	106.3	106.6	1.65	1.70	1.13	1.15
N-NPs (10 g N)	118.7	119.1	26.3	23.8	122.1	122.5	1.94	1.99	1.49	1.52
P-NPs (14 g P_2O_5)	114.8	115.2	22.3	21.0	120.7	121.1	1.83	1.88	1.29	1.35
K-NPs (40 g K_2O)	111.5	112.4	18.4	18.1	118.9	119.8	1.76	1.79	1.21	1.23
Fe-NPs (10 ppm)	110.9	111.1	22.0	22.4	110.4	110.6	1.88	1.92	1.30	1.33
Zn-NPs (5 ppm)	108.0	108.8	19.4	19.8	108.9	109.5	1.77	1.80	1.23	1.27
Mn-NPs (5 ppm)	106.7	107.6	17.3	17.7	107.7	108.1	1.71	1.77	1.15	1.20
New LSD at 5%	**1.1**	**1.2**	**2.0**	**2.1**	**1.2**	**1.3**	**0.03**	**0.03**	**0.03**	**0.04**

Overall, nano fertilization with essential macronutrients (N, P, K) and micronutrients (Fe, Zn, Mn) improves growth vigor of superior grapevines by promoting longer main shoots, more leaves per shoot, and increased leaf area, pruning wood weight and cane thickness. This is attributed to the higher nutrient use efficiency, better bioavailability, and targeted delivery of nutrients by nanotechnology-based fertilizers compared to traditional fertilizers. Nano nitrogen positively influences vegetative growth parameters in grapevines. Studies show that nano-N application increases main shoot length and leaf area significantly. This is attributed to the enhanced nutrient uptake efficiency and improved photosynthesis triggered by nitrogen, which stimulates auxin production promoting cell division and elongation, resulting in longer shoots and larger leaves. Increased nitrogen availability also supports greater leaf number and thicker canes due to enhanced protein synthesis and biomass accumulation (**Alimam and Hasan, 2023**). For example, nano-N application at higher concentrations (around 1000 ppm) in grapevines significantly increased leaf area and shoot length compared to lower doses (**Hamza and Sefan, 2020**). Nano-phosphorus plays a crucial role in carbohydrate synthesis and translocation, which directly affects vegetative plant growth parameters. Foliar and soil application of nano-P fertilizers enhances leaf number, leaf area, and cane thickness by improving energy transfer and metabolic activities within the plant. Phosphorus nano-fertilization is linked to better root development too, indirectly supporting vegetative growth above ground. Studies report that phosphorus fertilization increases leaf area and pruning wood weight due to improved nutrient availability for cell division and elongation (**Mohamed *et al.*, 2022; Aljubori *et al.*, 2024**). While, nano potassium fertilization significantly benefits vegetative growth traits such as shoot length, leaf number, leaf area, pruning wood weight, and cane thickness. Potassium activates enzymes involved in carbohydrate metabolism, protein synthesis, and chlorophyll production, which contribute to enhanced shoot elongation and leaf expansion. Potassium also maintains water and salt balance within cells, promoting cell turgor and growth. Nano-K application has shown increased shoot length, heavier pruning wood, and thicker canes in grapevines and other plants. For instance, nano-potassium at 150 mg/l induced notable improvements in shoot length and leaf area, attributable to better nutrient absorption and transport (**Mohamed *et al.*, 2022**).

Micronutrients are essential for photosynthesis and the enzymes that regulate plant metabolism. Zinc is an essential element for the optimal growth and reproduction of plants. The application of nano and chelated zinc resulted in a notable enhancement of vegetative growth traits in grapevines when compared to untreated specimens. The enhancement can be linked to zinc's critical function in enzyme and chlorophyll synthesis, which increases the net photosynthetic rate and promotes vegetative growth characteristics (**Al-Atrushy, 2021**). Reduced crop productivity and generally poor crop quality are the outcomes of plants having insufficient zinc availability (**Sarwar, 2011**). Auxin production is significantly impacted by zinc fertilizer, which improves cell division and mineral absorption and ultimately advances plant growth (**Cakmak, 2000**). According to **El-Tohamy and El-Greadly (2007**), zinc might work by boosting natural auxin (IAA), which would then promote cell growth and division. This could account for the increased growth-promoting hormone levels seen after applying zinc. Zinc is an essential component of many enzymes and a structural element or regulatory co-factor in a number of important plant biochemical processes. The pathways are responsible for the metabolism of carbohydrates, proteins, and auxins, as well as pollen formation, maintenance of cellular membrane integrity, and the ability to resist infections from specific pathogens (**Alloway, 2008**). Zinc nanoparticles (ZnNPs) exhibit an exceptional surface area-to-weight ratio, increased penetrability, and distinctive morphologies, making them smaller than traditional materials. The foliar application of ZnNPs may substantially influence the overall glucose content in canes, chlorophyll concentrations in leaves, and vegetative development traits. This will subsequently improve the yield per vine, the physical attributes of the berries, and their chemical makeup in Flame Seedless grapevines. Nano Zn particles may benefit grapevine application by decreasing the zinc needed in fertilizers and mitigating soil pollution caused by excessive chemical fertilizer usage (**El-Said *et al.*, 2019**).

Nano iron positively affects grapevine vegetative growth by improving chlorophyll synthesis and photosynthetic capacity, which enhances main shoot length and leaf area. Iron's crucial role in the creation of proteins, amino acids, and enzymes that support tissue growth and cell division and elongation may help to explain this. Plant height, stem diameter, and branch length all rise as a result of this improvement, which also raises cambium activity. Furthermore, increased leaf area and chlorophyll content lead to better nutrient uptake, which enhances vegetative development even more (**Kabota, 2005**). Iron is essential for various critical enzymes involved in the respiration process, including peroxidase, catalase, and cytochrome oxidase. The role of Fe in these compounds is essential for oxidation reactions, as it facilitates electron transfer during oxidation and reduction processes, which are critical for cellular metabolism (**Yasin, 2001; Focus, 2003**). Studies show foliar application of iron nanoparticles increases the availability of Fe within the plant, leading to more vigorous shoot growth, thicker canes, and higher pruning wood weight due to improved biomass accumulation. Iron nano-fertilizers also contribute to better stress tolerance, which supports sustained vegetative growth under adverse conditions (**El-Sayed and El-Taher, 2024**). Manganese nanoparticles enhance vegetative growth by improving enzyme activation and photosynthetic oxygen evolution. Mn nano-fertilizers promote leaf expansion and shoot growth, resulting in increases in main shoot length, leaf number, and leaf area. Improved nutritional status via Mn nano-application also results in greater pruning wood weight and cane thickness. Although fewer studies focus exclusively on Mn, combined micronutrient nano-fertilizers including Mn show consistent positive effects on grapevine vegetative vigor (**Al-Atrushy, 2019; Hosseinabad and Khadivi 2019; Shoug, 2022**).

3.2. Leaf pigments content mg/100 g F.W

The effects of varying concentrations of macro- and micronutrients, applied in both traditional and nano-forms to the leaves during the 2023 and 2024 seasons, on chlorophyll a, chlorophyll b, total chlorophyll, and total carotenoids (mg/100 g FW) relative to the control are presented in Table 2.

Table 2 demonstrate that the application of macro and micro nutrient fertilizers, in both traditional and nano forms at varying concentrations, significantly affected the levels of chlorophyll (a, b, and total) and total carotenoids in comparison to the untreated control. The highest mean values in individual form were observed for nano-N at 10 g N per vine, followed by nano-P and K for chlorophyll content, while total carotenoids recorded the highest mean values with nano-N followed by nano-Fe. The use of nano forms resulted in slightly higher in leaf pigments compared to traditional methods. The elevation of chlorophylls and total carotenoids content depended on the specific form and element utilized in each treatment. The findings indicated that the measured variables were influenced by different macro and micronutrients applied as a foliar spray, with macro nutrients demonstrating greater effectiveness. The control treatment demonstrated the lowest values in both seasons, whereas nano-N produced the highest values. As for the micro nutriment, it was found that using nano-Fe was more superior in increasing chlorophyll content than using other micro fertilizer, whether in nano or traditional forms. The other treatments exhibited intermediate values across both seasons.

Table (2). Impact of traditional and nano-fertilization on Superior grapevines leaf pigment content across 2023 and 2024 seasons

Characteristics / Treatments	Chlorophyll a mg/100 g FW		Chlorophyll b mg/100 g FW		Total chlorophyll mg/100 g FW		Total carotenoid mg/100 g FW	
	2023	2024	2023	2024	2023	2024	2023	2024
Control	3.0	3.2	1.4	1.5	4.4	4.7	1.6	1.7
Traditional-N (60 g N)	4.7	5.1	1.7	1.9	6.4	7.0	2.1	2.2
Traditional-P (84 g P_2O_5)	4.4	4.8	1.5	1.6	5.9	6.4	1.5	1.7
Traditional-K (240 g K_2O)	4.1	4.5	1.3	1.4	5.4	5.9	1.2	1.4
Traditional-Fe (100 ppm)	4.5	4.6	1.5	1.7	6.0	6.3	1.9	2.0
Traditional-Zn (50 ppm)	4.3	4.4	1.3	1.5	5.6	5.9	1.6	1.7
Traditional-Mn (50 ppm)	4.1	4.2	1.2	1.3	5.5	5.5	1.4	1.4
N-NPs (10 g N)	6.1	6.6	1.9	2.1	8.8	8.7	2.5	2.7
P-NPs (14 g P_2O_5)	5.7	6.1	1.7	1.8	7.4	7.9	1.8	2.3
K-NPs (40 g K_2O)	5.3	5.5	1.4	1.6	6.6	7.1	1.5	1.9
Fe-NPs (10 ppm)	4.9	5.1	1.8	1.9	6.7	7.0	2.2	2.3
Zn-NPs (5 ppm)	4.7	5.0	1.5	1.7	5.7	6.0	1.9	2.1
Mn-NPs (5 ppm)	4.4	4.6	1.3	1.5	5.7	6.1	1.7	1.8
New LSD at 5%	**0.2**	**0.2**	**0.2**	**0.2**	**0.3**	**0.3**	**0.2**	**0.3**

For vital metabolic functions and structural development, macronutrients such as potassium (K), phosphorus (P), and nitrogen (N) are necessary. Nano nitrogen strongly affects chlorophyll content in grapevine leaves. Nitrogen is a key component of chlorophyll molecules, especially influencing chlorophyll a and total chlorophyll content. Studies show that foliar application of nano-N significantly increases chlorophyll a, b, and total chlorophyll due to improved nitrogen use efficiency and enhanced synthesis of green pigments associated with photosynthesis (**Mohamed *et al.*, 2022; Abdullah Al-Salame and Al Douri, 2023**). Nitrogen is essential for the synthesis of amino acids, proteins, and chlorophyll, which promotes shoot growth, leaf development, and delays leaf senescence. Adequate nitrogen availability enhances shoot elongation, leaf expansion, and total biomass accumulation. Studies on Flame Seedless grapevines demonstrate that nitrogen supplementation increases both leaf quantity and surface area, thereby enhancing the photosynthetic system (**Bassiony *et al.*, 2018**). Phosphorus influences pigment content indirectly by supporting energy transfer and metabolic processes critical for chlorophyll biosynthesis. Nano phosphorus fertilization leads to a notable increase in chlorophyll a and b by improving the plant's metabolic activities and nutrient uptake. Research indicates that nano-P treatment enhances leaf pigment content, likely through improved ATP production and assimilation processes that sustain photosynthetic efficiency **(Mohamed *et al.*, 2022; Geng *et al.*, 2024**). Potassium plays a crucial role in regulating stomatal function, protein synthesis, and carbohydrate metabolism, which in turn affects berry size and ripening. Adequate potassium nutrition improves leaf turgor, increases leaf area, and facilitates the transport of photosynthates to developing shoots and clusters (**Mpelasoka *et al.*, 2003**). Nano potassium plays a vital role in maintaining chlorophyll and carotenoid stability in leaves by regulating enzyme activities involved in pigment biosynthesis and osmotic balance. Potassium nanofertilizers increase chlorophyll a, chlorophyll b, and carotenoid concentrations, supporting higher photosynthesis rates and protection against oxidative stress. Studies show foliar application of nano-K results in significant increases in leaf pigments, which improve photosynthetic capacity and overall plant vigor in grapevines (**Awad *et al.*, 2024; Masoud *et al.*, 2025a**).

Nano zinc positively influences pigments. It is essential for enzyme activation related to chlorophyll biosynthesis and auxin production, promoting chlorophyll a, b, and total chlorophyll accumulation. Zinc enhances photosynthetic efficiency in plants by sustaining the activity of carbonic anhydrase, which plays a role in chloroplast accumulation and chlorophyll production (**Li *et al.*, 2013; Mathpal *et al.*, 2015**). Foliar nano-Zn applications at low concentrations (1-2 ppm) significantly increase chlorophyll content and improve photosynthetic efficiency, which supports improved leaf pigment synthesis and stability. Nano zinc also boosts carotenoid content, providing antioxidant protection under stress conditions (**Shaaban, 2024; Akhondi *et al.*, 2025**). Nano iron plays a critical role in chlorophyll biosynthesis and photosynthetic electron transport, directly elevating chlorophyll a, b, total chlorophyll, and carotenoid levels. The initial enhancement in photosynthesis and vegetative development is attributed to the application of various forms of iron, including chelated and nano forms. Iron compounds are essential for the synthesis of enzymes and chlorophyll. Reduced iron levels in plants therefore result in decreased chlorophyll content, leaf chlorosis, poor vegetative development, and a lower net photosynthetic rate. Iron's function in increasing the number and size of chloroplasts may be the cause of the increase in chlorophyll content in leaves (**Prism *et al.*, 2011**). Iron serves as a cofactor in the synthesis of cytochromes and chlorophyll, essential for respiration and photosynthesis, and may also be a contributing factor (**Focus, 2003**). Studies show that nano iron treatments at optimal doses (e.g., 0.5 g/L nano green-Fe) increase chlorophyll a by over 50% compared to controls. Iron is vital for enzymes in chlorophyll synthesis and carotenoid biosynthesis pathways, enhancing pigment content and photosynthetic performance significantly. Nano-Fe treatments also alleviate iron chlorosis, stabilizing pigments and improving leaf greenness (**Al-Atrushy, 2019; El-Khawaga *et al.*, 2024**). Manganese nanoparticles improve photosynthetic pigment levels by activating enzymes involved in photosynthesis and pigment synthesis. Mn nano forms increase chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids, especially evident at early developmental stages in plants. Mn also acts as a cofactor for superoxide dismutase, protecting pigments from oxidative damage and supporting pigment stability. Foliar or seed priming with Mn nanoparticles results in enhanced pigment synthesis and antioxidant capacity in grapevines and other crops (**Salehi *et al.*, 2023**).

3.3. Nutritional status of leaves

Table 3 illustrate the effects of foliar application of macronutrient NPK or micronutrients Zn, Fe, and Mn at varying concentrations in form of nano and traditional one on the levels of nitrogen, phosphorus, and potassium in Superior grapevines, as well as iron, zinc, and manganese, respectively, during the 2023 and 2024 seasons.

The information regarding the nutrients content in leaves is detailed in Table (3), demonstrating the impact of traditional macro and micro fertilizers, as well as their nano-forms, at different concentrations in comparison to the control group. The control vines displayed the lowest leaf elements content in both seasons. The concentrations of nutrient in leaves increased when using nano-macro fertilizers compared to traditional fertilizers. The most advantageous results were obtained using nano-N, P, and K fertilizers, respectively, in contrast to traditional alternatives for the content of N, P and K, respectively, which recorded (2.13 -2.15% for N), (0.22 - 0.24% for P) and (1.32 - 1.34% for K) Despite this, the application of nano-N (10 g N/vine) resulted in the highest average values of Fe, Zn and Mn ppm, recorded values of 57.1- 59.2 ppm, 57.7 - 59.1 ppm and 56.9 - 57.1 ppm, respectively in 2023 and 2024 when compared to the other treatments relative to the control.

Table (3). Impact of traditional and nano-fertilization on Superior grapevines leaf macronutrient content across 2023 and 2024 seasons

Characteristics / Treatments	Leaf N%		Leaf P%		Leaf K%		Leaf Zn ppm		Leaf Fe ppm		Leaf Mn ppm	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Control	1.65	1.67	0.10	0.11	1.05	1.07	50.1	50.3	52.2	53.1	52.0	52.3
Traditional-N (60 g N)	1.72	1.75	0.14	0.15	1.10	1.11	55.0	56.1	55.8	56.1	55.4	55.9
Traditional-P (84 g P_2O_5)	1.66	1.68	0.19	0.22	1.15	1.17	50.2	51.4	50.9	52.3	50.1	51.2
Traditional-K (240 g K_2O)	1.54	1.59	0.15	0.17	1.28	1.30	48.3	49.7	48.0	48.9	47.3	48.1
Traditional-Fe (100 ppm)	1.63	1.66	0.11	0.12	1.09	1.10	50.5	52.5	53.4	53.9	53.2	53.4
Traditional-Zn (50 ppm)	1.57	1.59	0.15	0.16	1.13	1.14	53.2	55.4	51.6	52.5	48.7	50.0
Traditional-Mn (50 ppm)	1.52	1.54	0.12	0.13	1.22	1.25	51.6	52.1	50.2	51.0	50.6	51.5
N-NPs (10 g N)	2.13	2.15	0.17	0.18	1.15	1.17	57.1	59.2	57.7	59.1	56.9	57.1
P-NPs (14 g P_2O_5)	1.95	2.00	0.22	0.24	1.20	1.22	52.1	53.4	52.6	53.4	51.7	52.0
K-NPs (40 g K_2O)	1.86	1.80	0.18	0.21	1.32	1.34	50.3	51.4	49.6	50.1	49.2	50.0
Fe-NPs (10 ppm)	1.70	1.72	0.15	0.16	1.12	1.14	52.1	53.6	54.9	55.2	54.6	55.0
Zn-NPs (5 ppm)	1.66	1.67	0.21	0.22	1.16	1.18	55.0	56.1	53.0	54.2	50.0	50.4
Mn-NPs (5 ppm)	1.61	1.62	0.17	0.19	1.26	1.29	53.1	54.2	51.7	52.5	52.1	52.3
New LSD at 5%	**0.04**	**0.05**	**0.02**	**0.02**	**0.03**	**0.04**	**1.4**	**1.5**	**1.4**	**1.5**	**1.3**	**1.4**

Nano-formulations of macronutrient as N, P and K have been proven to enhance the mineral nutrient composition of grapevine through improved uptake, translocation, and utilization efficiency compared with conventional fertilizers. Foliar application of nano-nitrogen fertilizers in grapevines enhances nitrogen assimilation and stimulates chlorophyll synthesis, resulting in higher concentrations of N and associated micronutrients (Fe, Zn, and Mn) in leaves and berries (**Al-Jubori *et al.*, 2023**). In field experiments, nano-N formulations increased N content due to improved leaf penetration and slower nutrient release, maintaining longer availability within plant tissues. Study by **Yao *et al.* (2024**) reported that nitrogen nanofertilization enhances protein synthesis and iron mobilization, contributing to improved mineral balance and grape biochemical quality. Nano-phosphorus fertilizers significantly improve P content in grapevine tissue by increasing phosphorus mobility and uptake efficiency. Recent findings on nano-DAP (diammonium phosphate) formulations show that foliar sprays not only increased P in grains and leaves but also enhanced N and K uptake synergistically. In a study on nano-DAP (5 mL L^{-1} foliar) increased crop N uptake by up to 125 kg ha^{-1} and P uptake up to 26 kg ha^{-1} over controls, demonstrating enhanced nutrient acquisition efficiency and reduced fertilizer waste (**Reddy *et al.*, 2025**). Translating this mechanism to grapevine systems, nano-phosphorus fertilizer could similarly augment the absorption of N, P, and K while elevating Fe, Zn, and Mn due to improved root activity and enzymatic stimulation in the rhizosphere (**Al-Jubori *et al.*, 2023**). Potassium nano-fertilizers notably enhance plant N, K, Ca, and Mg concentrations due to better ionic exchange and translocation across tissues. Nano-K treatments lead to improved berry turgor, osmotic balance, and nutrient remobilization from roots to fruits. In grapevine studies **(Hamza *et al.*, 2019; Al-Jubori *et al.*, 2023**), foliar nano-NPK applications significantly increased total K and N accumulation, while indirectly augmenting Fe and Mn by improving photosynthetic capacity and enzymatic activity. Nano-K also promotes Zn movement within plant **v**ascular tissues due to its role in activating transport proteins **(Zheng *et al.*, 2025**).

As for the effect of micronutrient nano-fertilizers significantly improve the macro- and micro-mineral content of grapevine leaves. Foliar spraying with nano-iron oxide (Fe_2O_3-NPs) increases Fe concentration in leaves and berries by boosting chlorophyll formation, nitrogen assimilation, and root-to-shoot nutrient translocation (**El-Sayed and El-Taher, 2024**). According to **Jha *et al.* (2025**) and **Razzaq and Zhou (2025**), Fe-NPs enhance Fe, N, and Mn uptake by improving redox enzymatic activities such as ferric chelate reductase and nitrate reductase. In grapevines, 0.8 ppm Fe-NPs increased protein levels, N metabolism, and membrane stability under salt stress by stimulating antioxidant enzymes such as catalase and peroxidase (**Bidabadi *et al.*, 2023**). The enhanced Fe nutrition indirectly supports higher N and P accumulation due to improved metabolic energy flux in the xylem-phloem system. Nano-zinc fertilizer is the most effective micronutrient amendment for increasing N, K, and Zn levels in grapevine leaves and berries. **Masoud *et al.* (2025b**) reported that foliar nano-Zn application (50 ppm) in Thompson Seedless grapes yielded the highest berry N, Fe, and Zn concentrations, alongside improved cluster weight and total soluble solids. The mechanism lies in Zn's role in activating enzymes linked to carbohydrate and protein synthesis, which enhance nutrient uptake efficiency. **El-Sayed and El-Taher, (2024**) found in Flame Seedless vines treated with nano-ZnO (40 mg L^{-1}), which exhibited increased Zn, Fe, Mn, and P contents relative to chelated forms, demonstrating the nanoparticle advantage in nutrient penetration and stability. Nano-Zn also modulates root plasma membrane permeability, allowing simultaneous absorption of K^+, Fe^{2+}, and Mn^{2+} ions. Nano-manganese fertilizers promote both macro- and micro-mineral enrichment due to Mn's catalytic role in redox enzymes, especially those linked to photosystem II and nitrogen metabolism. Studies show that Mn-NPs significantly increase Fe, Zn, and N acquisition owing to their influence on chlorophyll-binding enzymes and oxidative phosphorylation balance (**Jha *et al.*, 2025**). The synergistic effect stems from Mn-activated decarboxylase enzymes, which boost organic acid metabolism and facilitate greater macro-element transport.

4. Conclusion

The findings of this study clearly demonstrate that nano-fertilization significantly enhances vegetative growth, pigment accumulation, and nutritional status in Superior grapevines when compared to traditional fertilization vines. Integrating nano-fertilization in viticulture practice is recommended for efficient nutrient use, improved plant performance, and enhanced fruit quality. Nano-N and nano-Fe should be prioritized for foliar application due to their consistent superior effects on both vegetative and reproductive traits.

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تحسين أداء كروم العنب "سوبيريور" باستخدام الأسمدة النانوية مقارنة بالأسمده التقليدية

على حسن على سيد و رضا حسين إبراهيم

قسم البساتين – كلية الزراعة – جامعة المنيا – مصر

الملخص العربى

بحثت التجربه في آثار إستخدام الرش الورقى بالعناصر الغذائية الكبرى و الصغرى في صورة أسمده نانويه و تقليدية على النمو الخضرى و المحتوى الكيميائى لكروم العنب "سوبيريور" خلال موسمى 2023 و 2024. من خلال 13 معامله صممت في قطاعات كامله العشوائية في 3 مكررات تضمنت العناصر الكبريى نيتروجين، فوسفور، بوتاسيوم، حديد، زنك و منجنيز في صوره نانويه و أخرى تقليديه مقارنه بالكنترول. من خلال التجربه وجد أن التسميد النانوى أدى إلى تحسن ملحوظ في طول الفرع الرئيسي(سم)، عدد الأوراق / فرع، مساحة الورقه سم^2، سمك القصب سم ، وزن خشب التقليم/كرمة كجم و محتوى الأوراق من الصبغات خاصة عند إستخدام التسميد النيتورجيني النانوي بمعدل 10 جم نيتروجين/ كرمه/سنه يليه التسميد بالحديد النانوى بمعدل 5 جزء في المليون/كرمه /سنه. بالإضافه إلى أن التسميد النانوى عزز العناصر الغذائية و أدى إلى تراكمها في الأوراق مقارنه بالتسميد التقليدي. و لذلك تدعم هذه الدراسة ضرورة دمج التسميد النانوى في زراعه كروم العنب للحصول على أعلى إستفادة من العناصر الغذائية و بالتالى تحسين نمو النبات و تعزيز جوده الكروم و خاصة عند إستخدام التمسيد النيتروجيني و الحديد النانوى على كروم عنب "سوبيريور" تحت نفس الظروف.

الكلمات المفتاحيه: عناصر كبري، صغرى، أسمده نانويه، نمو خضرى، محتوى كيميائى و عنب "سوبيريور"