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Integrated organic, chemical and nano-fertilization improves growth, nutrient status and productivity of Thompson Seedless grapevine

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Abstract

Viticulture is an important source of national income in exporting countries. Organic fertilizer (OF), chemical fertilizer (CF), and foliar nano-fertilizer (FNPs) play important roles in improving plant nutrition, growth, and yield. This study evaluated the combined soil application of chemical fertilizer (CF) and organic fertilizer (OF) at five ratios (100:0, 75:25, 50:50, 25:75 and 0:100) with foliar nano-fertilizer sprays containing Zn, Cu and Fe at four levels (100, 75, 50 and 25%). on growth, nutritional status, and productivity of Thompson Seedless grapevines over two seasons. The treatment 75% CF + 25% OF combined with 75% FNPs produced the highest yield and was statistically comparable to 100% FNPs for several growth and nutritional traits. This treatment also increased cluster weight and length. Furthermore, it achieved the highest fruit yield (42.2 and 43.6 kg per vine), compared to 50% CF + 50% OF with 75% FNPs (33.45 and 34.5 kg) and 100% CF + 0% OF with 25% FNPs (lowest at 15.85 and 15.82 kg) in the first and second seasons, respectively. This study highlights integrated strategies combining OF and FNPs as partial alternatives to CF for sustainable agriculture and reduced CF use.

Key words: *Vitis vinifera,* compost, bud burst, mineral content

Introduction

Grapes (*Vitis vinifera*) are a common deciduous fruit with high nutritional value, including soluble solids, multivitamins, procyanidins, and resveratrol (Zhu *et al.*, 2017), which enhance aroma and health benefits (Aubert and Chalot 2018). They can be consumed fresh or processed, expanding their uses (Zhu *et al.*, 2015). In 2023, global production reached about 72.5 million tons, using 6,595,680 hectares. Egypt contributed 2.65% of the world's production and 1.26% of the area, with a yield per hectare that was 47.9% above the global average (FAO, 2025).

The global population is projected to reach about 9 billion (Singh *et al.*, 2023), which will require more crop production, even though soil and water resources are limited. New agricultural areas often have mineral shortages, low organic matter, and problems like salinity, drought, and alkalinity. At the same time, the fertility of existing soils is decreasing. Arid and semi-arid regions, covering over 30% of the Earth's surface (Taalab *et al.*, 2019; Bolan *et al.*, 2023) and more than a quarter of Egypt's soils, have high pH levels (7–8.5), low water-holding capacity, and sandy textures (Abou Hussien *et al.*, 2021).

As a result, soils in these areas have low organic matter, requiring yearly additions due to limited availability, rapid decomposition from high temperatures, and unsustainable farming practices (like intensive tillage, high-yielding varieties, monoculture, low nutrient availability, and imbalanced fertilization). Therefore, using both organic and inorganic fertilizers is necessary (Yadav *et al.*, 2023; Fertilizer practices include organic fertilizers (OF) and chemical fertilizers (CF). While optimal CF boosts production, excessive use causes soil degradation, water pollution, and high costs (Liu *et al.*, 2011; Sierra *et al.*, 2015). In contrast, OF supports sustainable development by improving soil structure, fertility, and microbial activity (Bajeli *et al.*, 2016) that this process provides a variety of nutrients (Fallah *et al.*, 2018). Moreover, as Weisany *et al.* (2016) demonstrated, it enhances mineral uptake, improves soil health, and helps break down organic matter.

Bajeli *et al.* (2016) reported that OF increased quality and production of Japanese mint (*Mentha arvensis* L.). Studies have shown that combining composted farmyard manure (CF) and organic fertilizer (OF) can improve crop yields in various plants, such as olive trees (Hamed *et al.*, 2025), mango trees (Shaban *et al.*, 2025), peach trees (Fayed *et al.*, 2019), and grapevines (Wu *et al.*, 2024). Using both CF and OF together has been found to increase grape yields (Ali *et al.*, 2021; Li *et al.*, 2022). and boost the availability of nitrogen (N), phosphorus (P), and potassium (K) compared to using CF alone (Wu *et al.*, 2024). This method also contributes to the improvement of soil organic matter and overall soil fertility (Liang *et al.*, 2014; Xie *et al.*, 2017; Wang *et al.*, 2017; Yang *et al.*, 2019).

Nanotechnology presents promising interdisciplinary applications in agriculture (Debashis and Lalrinchhani, 2021; Kumar *et al.*, 2024; Singh *et al.*, 2024a), involving particles that are 1–100 nm in size (Saleh, 2020). These particles have a larger surface area and unique properties (Joudeh and Linke, 2022).

Nano-fertilizers offer a sustained release of minerals, in contrast to conventional fertilizers (Seleiman *et al.*, 2020), and they enhance nutrient uptake (Ghorbani *et al.*, 2024; Singh *et al.*, 2024b), diminish environmental contamination, and alleviate various stressors (Kashyap *et al.*, 2017). Aazami *et al.* (2022) recently observed that Nano-Fe application resulted in increased dry weight and chlorophyll content in Sultana grapes.

Micronutrients such as Fe, Zn, and Cu are critical for plant development, particularly in soils characterized by low fertility and high pH levels. Iron is involved in chlorophyll biosynthesis, respiration, and redox processes (Ahmad *et al.*, 2024), as well as DNA synthesis, photosynthesis, and nitrogen reduction (Rout and Sahoo, 2015; Grotz and Guerinot, 2006), functioning as a cofactor for enzymes including cytochrome oxidase and iron-sulfur proteins (Guerinot, 1994) and in the synthesis of plant hormones (Siedow, 1991). Zinc, on the other hand, activates enzymes such as polymerases and dehydrogenases, and it also facilitates photosynthesis, cell division, and protein synthesis (Makhasha *et al.*, 2024). Cu supports respiration, photosynthesis, and antioxidants; Cu NPs enhance biochemical processes and yield (Seleiman *et al.*, 2020; Nair *et al.*, 2014), while Cu and Zn NPs boost defense enzymes (Rashedy *et al.*, 2024; Abd El-Aziz *et al.*, 2025).

Therefore, the aim of this study was to evaluate the combined replacement of chemical fertilizers with organic compost and foliar Zn–Fe–Cu nanoparticles on improving Thompson seedless vines growth, nutritional status and productivity under sandy alkaline conditions in Egypt.

Materials and methods

Plant material and soil analysis: This study was carried out on Thompson seedless grapevines during 2021 and 2022 seasons. The vine was 13-years old, uniform in growth and was planted at 2 x 3m apart in a private vineyard located at Al-Khataba, Menoufia Governorate (Latitude. 30° 22′ 31″ North; Longitude. 30° 50′ 23″ east ; Elevation. 14 metres). The soil was sandy soil (Table 1&2) and well drained with a water table deeper than two meters. After winter pruning which carried out in the first week of January via cane pruning system each vine had 64 fruiting eyes (4 fruiting canes x 14 eyes).

Treatments: The experiment was arranged in two way factorial with, three replicates with 3 vines for each one (9 vines per treatment). The experiment consist of the following soil application of CF+OF at five levels 100%+0%, 75%+25%, 50%+50%, 25%+75% and 0%+100% in the main plot, incorporated with four FNPs levels in sub plot with NPs of Cu, Fe and Zn at four levels 25, 50, 75 and 100%. CF was divided into four doses (flowering, fruit set, one month later, two months later). According to local farmer practice CF level at 100% per vine was N:P:K at 60:40:120g, respectively. Regarding OF, it was added once at the fall season (November) in the previous year in two furrows (Table 3), 100% OF was 10.34 kg per vine. With regard to FNPs Fe : Cu : Zn was 125 : 6.66 : 62.5 mg L^{-1} in 100% level. FNPs was sprayed three times after fruit set, one month later and two months later using 0.1% tween 80 as surfactant.

Nano zinc, iron, and copper synthesis: Nanoparticles were obtained by the top to bottom molecular chemical method (Daneshvar *et al* 2007 and Mahmoud *et al* 2020). Zn NPs was prepared from an aqueous solution of $ZnCl_2$. Sodium hydroxide solution was added slowly in a molar ratio of 1:2 under vigorous stirring for 8 h. The obtained precipitate was filtered and washed thoroughly with deionized water in a mixed water/toluene system using a high-speed stirrer, and then washed again with deionized water alone for 3 h. The precipitate was dried in an oven at 100 °C, (2.75 g nano-particles powder) then exposed to 1.5 psi of pressure for 3 days discontinuously (7 h per day).

Fe NPs was prepared with little modification from magnetite (Fe_3O_4) of Fe^{3+} and Fe^{2+} at a molar ratio of 3:2 by reduction–precipitation in aqueous ammonia (0.3 mol L^{-1}) and coated tetra methyl ammonium hydroxide under vigorous stirring for 2 h using magnetic stirring, precipitate was then separated by magnetic filtration using a permanent magnet, and washed with distilled water until a neutral pH (Mahmoud and Taha, 2018).

Cu NPs was prepared by CuO from (reagents of analytical grade (Sigma, USA)) its precursor chemical compound $CuSO_4$. NPs was obtained by chemical precipitation method and physical combined methods (Zhang *et al.*, 2014), with some modifications. 1 M NaOH solution was added slowly (drop by drop) to aqueous solution of $CuSO_4$ in a molar ratio of 1:3 under vigorous stirring for 10 h, discontinuously (2 days). The obtained precipitate was then mixed with 2 N citric acid monohydrate for 3 h, the obtained precipitate was filtered and washed thoroughly with deionized water in a mixed water/hexane system using a high-speed stirrer, and then washed again with deionized water alone for 2 h. The precipitate was finally dried in an oven at 108 °C for 24 h, and then exposed to 1.5 psi of pressure for5 days, discontinuously (6 h per day).

NPs characterization: Scanning electron microscopy was used to determine the size and morphology of Zn NPs, Fe NPs and Cu NPs.

Vegetative parameters: Vegetative growth parameters were measured by standard procedures. The proportion of the burst buds within a vine was used to determine the percentage of bud

Table 1. Physical properties of the experimental farm soil

Texture Class	Clay (%)	Silt (%)	F. Sand (%)	C. Sand (%)	HC (cm/h)	TP (%)	BD (g/cm³)	AW	PWP	FC
Sand	3.05	4.25	12.50	80.20	6.25	52.8	1.52	4.45	4.10	8.55

FC: Field capacity; PWP: Permanent wilting point; AW: Available water; BD: Bulk density; TP: Total porosity; HC: Hydraulic conductivity.

Table 2. Chemical properties of the experimental farm soil

Organic matter (%)	EC (dS/m)	pH (1:2.5)	Soluble anions (meq L^{-1})				Soluble cations (meq L^{-1})			
			Cl^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	Na^+	K^+	Mg^{2+}	Ca^{2+}
0.2	1.68	7.68	3.6	11.50	0	1.7	0.58	0.39	4.18	5.20

Table 3. Chemical properties of compost

N (%)	P (%)	K (%)	Cu (ppm)	Zn (ppm)	Fe (ppm)	Organic matter (%)	Ash (%)	Moisture (%)	EC (dS/m)	pH (1:10)
0.58	0.39	1.16	161	36	1226	57	23	31	3.56	6.74

burst. Similarly the percentage of fruiting buds was calculated by counting the number of fruitful buds and calculating them as a percentage of the total burst buds.

To measure the growth of the shoots, ten principal shoots were randomly taken in each vine and their lengths measured in the first week of September. The leaf area was measured at the active growing period by picking twenty mature and fully developed leaves per vine. The samples of these leaves were taken in opposite positions to the initial cluster on each shoot, as per Pereira *et al.* (2013). The area of the leaf was then determined according to the empirical equation suggested by Ahmed and Morsy (1999):

$La = 0.40 (0.79 \times w^2) + 15.23$, in which w is the maximum leaf width.

Chemical analysis of leaf petioles: Representative petioles sample were taken and analyzed for macro and micronutrients after washing in sequence with tap water, 0.01 N HCl acidified by distilled water, respectively and then dried in a ventilated oven (70 °C for 72 h) till constant weight. The plant samples were ground (stainless steel mill) and kept in plastic containers for the determination of N using modified micro Kjeldahl (Pregl, 1945), as well as P using spectrophotometer (Chapman and Pratt, 1961) and K using Flame Photometry (Brown and Lilleland, 1946). Zn, Cu and Fe were determined using Atomic absorption spectrophotometer PerkinElemer model 1100 (Jackson 1973).

Yield measurements: The harvesting took place when TSS / acid ratio in the berries of the check treatment reached at least 25 : 1 (at the last week of July in both seasons). The yield (kg) of each vine was recorded and clusters No. per vine then the average cluster weight (g) were recorded.

Statistical analysis: The design of this experiment was in split plot design. The treatments layout in a randomized complete block design. The main plot factor was CF and OF in the main plot with five levels, while FNP was foliar application of Nano particles with four levels. Total treatments was 5 (CF + OF)× 4 (FNP)= 20, with 3 replicates (3 vines) for each treatment. Each treatment contains 9 vines, with total of (20 x 9) 180 vines. The experimental unit was three vines per replicate. The data were averaged per treatment. Analysis of variance (ANOVA) was calculated via MSTAT-C software package (Freed *et al.*,1990). Treatments means were compared by the least significant difference test at level of $p < 0.05$ (Snedecor and Cochran, 1989). Each season was analysed separately.

Results and discussion

NPs characterization: The size and shape of nanoparticles were detected directly by scanning electron microscopy it can be observed that Zn NPs (Fig. 1A) size was 24.3-25.4 nm while, Fe NPs (Fig. 1B) size was 12.1-27 nm and Cu NPs (Fig. 1C) size was 19.5-23.3 nm.

Vegetative parameters

Bud burst and fruiting bud %: Regarding bud burst and fruitful bud percentages, the data presented in Table 4 show the effect of soil application of chemical fertilizers (CF) and organic fertilizers (OF) and foliar application of nanoparticles (FNPs) on the bud burst of Thompson seedless grapevines. It can be noted that the highest significant bud burst % was recorded by 25% CF + 75% OF and 50% CF + 50% OF, both combined with 100%, 75%, and 50% FNPs, with no significant difference between the highest two FNP levels.

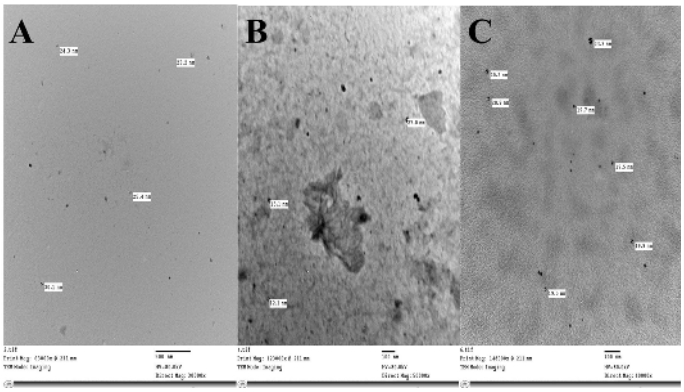


Fig.1. Scanning electron microscopy (SEM) for Zn NPs (A), Fe NPs (B) and Cu NPs (C).

The data in Table 4 also illustrates the impact of soil application of CF, OF, and FNPs on the fruitful bud % of Thompson seedless grapevines. It can be observed that the highest significant fruitful bud % was recorded by 75% CF + 25% OF and 50% CF + 50% OF combined with 100%, 75%, and 50% FNPs. The increase in bud burst % and fruitful bud % is mainly due to the OF applied early in the previous fall season, which may activate soil microbes and warm the soil environment, thereby supporting bud burst.

Table 4. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on bud burst and fruitful bud percentage of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Bud burst%		Fruitful bud percentage	
		2021	2022	2021	2022
100%CF + 0%OF	100%	71.33	72.46	45.68	46.03
	75%	70.53	71.66	45.33	45.56
	50%	70.00	71.30	45.26	45.70
	25%	69.00	71.03	45.03	45.10
75%CF + 25%OF	100%	71.16	71.90	49.70	50.26
	75%	70.66	71.63	49.46	53.00
	50%	69.33	70.13	49.43	50.16
	25%	68.50	69.53	48.30	48.83
50%CF + 50%OF	100%	73.50	71.90	49.70	48.60
	75%	72.80	71.63	49.46	48.43
	50%	71.50	70.13	49.43	48.10
	25%	71.00	69.53	48.3	47.60
25%CF + 75%OF	100%	73.86	74.70	46.26	46.80
	75%	72.83	73.50	46.16	46.33
	50%	72.06	72.86	45.93	46.33
	25%	71.50	72.46	45.83	46.50
0%CF + 100%OF	100%	70.93	71.73	45.20	45.73
	75%	70.20	70.93	44.80	45.40
	50%	69.33	70.36	44.50	45.16
	25%	69.00	69.86	44.20	44.66
New LSD at 5% A (Soil)		0.81	0.776	0.21	1.06
New LSD at 5% B (Foliar)		0.50	0.42	0.27	0.77
New LSD at 5% AxB		1.30	1.09	0.71	1.97

CF= Chemical fertilizers, OF= Organic fertilizers, NPs Nanoparticles,

Shoot length and leaf area: Regarding shoot length and leaf area, the data presented in Table 5 demonstrate the effect of soil application of CF, OF, and FNPs on the shoot length of Thompson seedless grapevines. The highest significant shoot length was recorded by 75% CF + 25% OF combined with 100%, 75%, and 50% FNPs, followed by 75% CF + 25% OF combined with 25% FNPs, and then 50% CF + 50% OF combined with 100% and 75% FNPs.

Table 5 also illustrates the impact of soil application of CF, OF, and FNPs on the leaf area of Thompson seedless grapevines. The highest significant leaf area was recorded by 75% CF + 25% OF

combined with 100%, 75%, and 50% FNPs, alongside 50% CF + 50% OF with different FNP treatments.

The high level of nano-fertilizers increased both shoot length and leaf area. This could be due to the nutrients satisfying the vine's needs, supplying the necessary elements to complete the growth cycle, and enhancing the release of growth regulators, thereby helping to increase shoot length and leaf area.

Additionally, the outcome data provides a reasonable biological mechanism for how the combination of nano-elements and organic matter (compost) led to significant increases in growth parameters over the control. These advantageous effects arise from providing plants with a source of nitrogen, essential macro- and micronutrients, and hormone-like substances, while simultaneously improving water availability and retention.

These results are similar to those obtained by Derosa *et al.* (2010), Debashis and Lalrinchhani (2021) and Mahmoud *et al.* (2020). Jaseem *et al.* (2025) recorded that the application of NPK incorporated with nano-fertilizers improved the growth of grapes. Moreover, Fayed *et al.* (2025) reported an increase in vegetative growth, leaf nutrients, total amino acids, and total carbohydrates of young plum trees.

Table 5. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on shoot length and leaf area of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Shoot length cm		Leaf area cm^2	
		2021	2022	2021	2022
100%CF + 0%OF	100%	162.55	163.56	140.16	141.00
	75%	161.66	162.86	138.13	138.40
	50%	160.33	161.56	136.76	136.86
	25%	156.56	157.90	135.36	136.23
75%CF + 25%OF	100%	184.33	195.81	144.70	145.53
	75%	183.83	189.13	144.00	147.96
	50%	180.40	185.06	142.60	142.90
	25%	176.93	179.76	140.80	141.33
50%CF + 50%OF	100%	171.63	185.06	142.40	143.06
	75%	170.20	183.40	142.96	143.30
	50%	166.10	180.33	143.83	143.70
	25%	164.30	179.46	143.50	143.60
25%CF + 75%OF	100%	164.66	175.03	142.16	142.60
	75%	163.93	173.80	141.70	141.90
	50%	160.43	169.13	141.53	142.10
	25%	158.40	162.73	141.23	141.83
0%CF + 100%OF	100%	154.43	160.20	137.53	137.30
	75%	150.76	157.36	137.06	137.33
	50%	149.40	155.96	136.63	136.80
	25%	148.53	154.63	136.20	136.36
New LSD at 5% A (Soil)		1.23	1.35	1.30	1.40
New LSD at 5% B (Foliar)		0.95	1.01	0.95	0.92
New LSD at 5% AxB		3.21	3.27	1.64	2.75

The combined application of CF, OF, and FNPs recorded the highest vegetative growth (shoot length and leaf area) of Thompson seedless grapevines. This may be due to OF increasing soil fertility, water-holding capacity, and nutrient availability. Furthermore, CF provides quick and direct nutrients for the vines in an absorbable form, while FNPs provide fast nutrients directly to the leaves.

These results are in line with Ma *et al.* (2019), who found that the application of chelated Fe and Cu (1000 ppm) improved leaf photosynthesis of the 'Kyoho' grape. Similarly, Fayed *et al.* (2019) reported an increase in peach vegetative growth when treated with different OF forms.

Berry setting (%) and number of clusters per vine: Regarding berry setting % and the number of clusters per vine, the data in Table 6 show the impact of soil application of CF, OF, and FNPs on the berry setting % of Thompson seedless grapevines. The highest significant value was recorded by 75% CF + 25% OF combined with different levels of FNPs, and 50% CF + 50% OF combined with 100% and 75% FNPs.

Table 6 also shows the impact of soil application of CF, OF, and FNPs on the number of clusters per vine. Generally, there were no significant differences between the different treatments for the number of clusters per vine, except for 0% CF + 100% OF, which recorded the lowest value in the first season.

The increase in Thompson seedless fruit set with the combined application of CF, OF, and FNPs may be due to increased nutrient availability, which stimulates more growth and enzyme activity necessary for increasing fruit set %. These results are in agreement with Hamed *et al.* (2025), who reported an improvement in olive fruit set due to OF.

On the other hand, the number of clusters per vine was affected more by the number of buds kept on the vine after pruning, which was fixed in all treatments. Therefore, the differences between them were generally not significant. In this regard, Hamed *et al.* (2025) reported an improvement in flowering and fruit set of olive trees treated with organic fertilization.

Table 6. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on berry setting% and number of cluster of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Berry setting (%)		Number of clusters/vine	
		2021	2022	2021	2022
100%CF + 0%OF	100%	6.50	6.66	29	29
	75%	6.45	6.50	29	29
	50%	6.42	6.36	29	28
	25%	6.31	6.33	28	28
75%CF + 25%OF	100%	7.28	7.56	28	29
	75%	7.43	7.70	28	29
	50%	7.33	7.46	28	28
	25%	7.13	7.43	27	28
50%CF + 50%OF	100%	7.30	7.53	27	28
	75%	7.13	7.30	28	28
	50%	6.83	6.83	28	28
	25%	6.30	6.50	26	27
25%CF + 75%OF	100%	5.73	5.83	27	28
	75%	5.66	5.83	28	28
	50%	5.30	5.43	28	29
	25%	5.06	5.16	27	28
0%CF + 100%OF	100%	4.93	5.16	28	28
	75%	4.90	5.20	26	28
	50%	4.83	5.00	27	28
	25%	4.80	5.06	25	27
New LSD at 5% A (Soil)		0.22	0.18	1.01	1.16
New LSD at 5% B (Foliar)		0.12	0.13	0.81	1.04
New LSD at 5% AxB		0.29	0.34	2.0	2.0

Leaf nutritional status: Regarding leaf nutritional status, the data presented in Table 7 show the impact of soil application of CF, OF, and FNPs on the leaf N % of Thompson seedless grapevines. The highest significant leaf N % was recorded by 75% CF + 25% OF accompanied by 100% and 75% FNPs, then combined with 50% FNPs, followed by 100% FNPs combined with 100% CF + 0% OF, and 50% CF + 50% OF.

Table 7 also illustrates the effect of soil application of CF, OF, and FNPs on the leaf P % of Thompson seedless grapevines. The

highest significant leaf P % was recorded by 100% CF + 0% OF and 75% CF + 25% OF accompanied by 100% FNPs.

Furthermore, Table 7 illustrates the impact of soil application of CF, OF, and FNPs on the leaf K % of Thompson seedless grapevines. The highest significant leaf K % was recorded by 100% CF + 0% OF accompanied by 100% and 75% FNPs, and 75% CF + 25% OF accompanied by 100% and 75% FNPs, followed by 50% CF + 50% OF with 100% FNPs.

Table 7. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on leaf N, P and K of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Leaf N%		Leaf P%		Leaf K%	
		2021	2022	2021	2022	2021	2022
100%CF + 0%OF	100%	2.06	2.30	0.53	0.52	1.98	2.00
	75%	1.95	2.03	0.51	0.51	1.94	1.94
	50%	1.85	2.00	0.49	0.48	1.92	1.91
	25%	1.82	1.87	0.47	0.46	1.82	1.87
75%CF + 25%OF	100%	2.46	2.66	0.53	0.51	1.97	1.94
	75%	2.30	2.53	0.49	0.47	1.91	1.94
	50%	2.08	2.26	0.49	0.46	1.79	1.87
	25%	1.92	2.03	0.47	0.46	1.63	1.80
50%CF + 50%OF	100%	2.01	2.20	0.47	0.45	1.84	1.92
	75%	1.93	2.06	0.45	0.44	1.79	1.82
	50%	1.89	1.98	0.45	0.44	1.75	1.77
	25%	1.82	1.96	0.43	0.43	1.57	1.63
25%CF + 75%OF	100%	1.83	1.98	0.42	0.39	1.71	1.73
	75%	1.78	1.92	0.40	0.39	1.63	1.70
	50%	1.58	1.72	0.39	0.37	1.58	1.60
	25%	1.48	1.66	0.36	0.35	1.50	1.53
0%CF + 100%OF	100%	1.46	1.60	0.30	0.29	1.41	1.48
	75%	1.43	1.56	0.29	0.28	1.38	1.45
	50%	1.43	1.56	0.27	0.26	1.36	1.42
	25%	1.30	1.40	0.26	0.25	1.20	1.37
New LSD at 5% A (Soil)		0.08	0.07	0.01	0.01	0.09	0.08
New LSD at 5% B (Foliar)		0.05	0.09	0.01	0.01	0.04	0.05
New LSD at 5% AxB		0.13	0.23	0.03	0.03	0.11	0.12

The data presented in Table 8 show the effect of soil application of CF, OF, and FNPs on the leaf Zn content (ppm) of Thompson seedless grapevines. The highest significant leaf Zn was recorded by 75% CF + 25% OF combined with 100% and 75% FNPs, alongside 100% CF + 0% OF combined with 100% and 75% FNPs.

Table 8 also shows the impact of soil application of CF, OF, and FNPs on the leaf Cu content (ppm) of Thompson seedless grapevines. The highest significant leaf Cu was recorded by 75% CF + 25% OF accompanied by 100% and 75% FNPs, followed by 50% CF + 50% OF combined with 100% FNPs. Table 8 also illustrates the effect of soil application of CF, OF, and FNPs on the leaf Fe content (ppm) of Thompson seedless grapevines. The highest significant leaf Fe was recorded by 75% CF + 25% OF combined with 100% and 75% FNPs, alongside 50% CF + 50% OF combined with 100% FNPs, followed by 100% CF + 0% OF combined with 100% and then 75% FNPs.

The increase in leaf mineral content due to the combined application of CF, OF, and FNPs may result from increasing soil fertility and nutrient availability, as well as the direct increase in leaf nutrients provided by FNPs.

These results are in line with Fayed *et al.* (2019), who reported an increase in peach leaf mineral content due to the application of different OF forms. More recently, Shaban *et al.* (2025) reported an increase in mango leaf mineral content due to biochar application. Additionally, Nano Fe improved the plant dry weight and chlorophyll of the 'Sultana' grape (Aazami *et al.*, 2022). Organic fertilizers also increase available N, P, and K in the soil compared to CF (Wu *et al.*, 2024) and play a vital role as a contributor to soil organic matter, improving soil fertility and characteristics in grapes (Liang *et al.*, 2014; Wang *et al.*, 2017; Xie *et al.*, 2017; Yang *et al.*, 2019).

Table 8. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on leaf Zn, Cu and Fe of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Leaf Zn (ppm)		Leaf Cu (ppm)		Leaf Fe (ppm)	
		2021	2022	2021	2022	2021	2022
100%CF + 0%OF	100%	60.23	59.80	10.13	10.31	217.67	221.00
	75%	60.13	59.77	9.57	9.90	210.33	212.67
	50%	59.07	58.63	9.45	9.44	207.00	207.67
	25%	58.53	58.28	9.30	9.41	196.00	201.00
75%CF + 25%OF	100%	61.23	60.75	10.86	11.10	249.00	252.33
	75%	60.52	60.57	10.55	10.79	245.67	248.67
	50%	59.60	59.87	10.42	10.56	240.00	242.33
	25%	58.03	58.47	9.29	9.48	232.00	236.33
50%CF + 50%OF	100%	57.67	58.10	10.50	10.35	249.67	250.33
	75%	57.40	57.60	10.08	9.99	244.00	245.33
	50%	56.60	57.07	9.12	9.23	241.33	243.33
	25%	56.28	56.60	8.80	9.03	237.67	239.67
25%CF + 75%OF	100%	56.87	57.03	8.58	8.78	171.67	176.00
	75%	56.23	56.57	8.46	8.53	166.00	171.33
	50%	55.10	55.03	8.25	8.46	161.33	167.00
	25%	53.97	54.23	8.14	8.30	160.67	163.00
0%CF + 100%OF	100%	52.77	52.47	7.61	7.76	138.33	140.67
	75%	50.80	51.23	7.45	7.60	133.00	139.33
	50%	49.17	49.33	7.30	7.36	130.33	135.33
	25%	47.93	48.53	7.30	7.23	129.33	133.00
New LSD at 5% A		0.50	0.50	0.31	0.42	3.00	3.12
New LSD at 5% B		0.29	0.27	0.10	0.18	2.11	1.81
New LSD at 5% AxB		0.74	0.70	0.25	0.46	5.40	4.64

Cluster weight and yield: Regarding cluster weight and yield, the data presented in Table 9 show the impact of soil application of CF, OF, and FNPs on Thompson seedless grapevines. The highest significant cluster weight was recorded by 75% CF + 25% OF accompanied by 75% and 100% FNPs, followed by 75% CF + 25% OF combined with 50% FNPs, and 50% CF + 50% OF accompanied by 100% and 75% FNPs.

Table 9 also illustrates the effect of soil application of CF, OF, and FNPs on the vine yield of Thompson seedless grapevines. The highest significant vine yield was recorded by 75% CF + 25% OF combined with 100% and 75% FNPs, followed by combinations with 50% FNPs. This was followed by 50% CF + 50% OF combined with 100% FNPs, while the lowest fruit yield was recorded by 100% CF + 0% OF combined with 25% FNPs which recorded the lowest yield 15.85 and 15.82 kg, respectively.

The increase in yield and growth parameters due to mixing of CF + OF may be due to that, CF provides readily available NPK, While OF working as a slow release fertilizers which improves organic matter, soil structure, water retention and microbial activity. Also, foliar Zn, Fe and Cu may improve enzyme activity, chlorophyll formation and photosynthesis. In contrast, excessive replacement of CF with OF may reduce immediate nutrient availability which explain low effect of 100% OF on Cluster weight and yield. It was noticed that 75% CF + 25% OF + 75% FNPs performed better than 100% FNPs in some yield traits which may be due to that OF contains many microelements (Table 3) as well as soil (Table 2) which provide the vines requirements of this nutrients in enough amounts.

Table 9. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on cluster weight and yield of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Cluster weight (g)		Yield (kg vine^{-1})	
		2021	2022	2021	2022
100%CF + 0%OF	100%	763.33	760.00	22.14	22.05
	75%	756.10	752.10	21.93	21.81
	50%	632.83	630.50	18.35	17.86
	25%	566.30	565.30	15.86	15.82
75%CF + 25%OF	100%	1486.36	1480.90	41.64	42.97
	75%	1507.06	1503.60	42.19	43.61
	50%	1253.63	1249.03	35.10	34.98
	25%	921.83	921.26	24.89	25.77
50%CF + 50%OF	100%	1239.33	1233.46	33.45	34.53
	75%	1178.40	1172.53	32.95	32.81
	50%	1016.80	1011.00	28.47	28.31
	25%	973.93	975.83	25.35	26.36
25%CF + 75%OF	100%	975.92	977.20	26.35	27.36
	75%	973.57	971.96	27.26	27.23
	50%	967.14	966.83	27.08	28.04
	25%	916.67	917.93	24.75	25.72
0%CF + 100%OF	100%	870.93	868.43	24.40	24.33
	75%	862.13	862.36	22.41	24.13
	50%	839.16	837.06	22.66	23.43
	25%	829.86	826.53	20.75	22.29
New LSD at 5% A (Soil)		22.98	23.71	1.42	1.33
New LSD at 5% B (Foliar)		15.96	15.41	0.90	1.17
New LSD at 5% AxB		40.83	39.42	2.31	3.00

Table 10. Effect of chemical and organic soil fertilization combined with foliar application of nanoparticles of Cu, Fe, and Zn on cluster length and width of Thompson seedless grapevine

Soil fertilization	Foliar NPs	Cluster length cm		Cluster width cm	
		2021	2022	2021	2022
100%CF + 0%OF	100%	24.83	24.93	15.27	14.83
	75%	24.33	24.70	14.50	14.03
	50%	24.07	24.60	14.10	13.67
	25%	23.83	24.17	13.77	13.47
75%CF + 25%OF	100%	26.17	26.83	16.00	15.50
	75%	27.00	27.00	15.80	15.33
	50%	25.83	26.17	15.40	14.83
	25%	25.17	25.67	14.83	14.17
50%CF + 50%OF	100%	25.87	25.87	15.50	14.93
	75%	25.33	25.33	15.07	14.33
	50%	24.67	24.67	14.83	14.17
	25%	24.17	24.17	14.33	13.83
25%CF + 75%OF	100%	23.93	24.33	14.17	13.67
	75%	23.80	24.17	14.00	13.33
	50%	23.77	24.00	13.77	13.33
	25%	23.33	23.67	13.77	13.17
0%CF + 100%OF	100%	23.67	23.83	13.67	13.83
	75%	23.33	23.67	13.43	13.53
	50%	23.17	23.33	13.33	13.50
	25%	23.00	23.33	13.17	13.33
New LSD at 5% A (Soil)		0.25	0.12	0.18	0.27
New LSD at 5% B (Foliar)		0.25	0.19	0.25	0.30
New LSD at 5% AxB		0.64	0.48	0.63	0.77

Cluster length and width: Regarding cluster length and width, the data presented in Table 10 show the effect of soil application of CF, OF, and FNPs on the cluster length of Thompson seedless grapevines. The highest significant cluster length was recorded by 75% CF + 25% OF combined with 75% and 100% FNPs, followed by 75% CF + 25% OF combined with 50% and 25% FNPs, alongside 50% CF + 50% OF combined with 100% and 75% FNPs.

Table 10 also shows the impact of soil application of CF, OF, and FNPs on the cluster width of Thompson seedless grapevines. The highest significant cluster width was recorded by 75% CF + 25% OF combined with 100%, 75%, and 50% FNPs, alongside 50% CF + 50% OF with 100% FNPs.

The increase in fruit yield and quality due to the combined application of CF, OF, and FNPs may be due to increased mineral content, vegetative growth, and fruit set, which led to increased vine productivity. These results are in agreement with Hamed *et al.* (2025), who recorded an improvement in olive yield and fruit quality due to OF.

Additionally, the foliar application of micronutrients (Fe, Zn, and B) improved the yield, bunch number, bunch weight, and bunch length of Thompson seedless grapes (Ali *et al.*, 2021). The combined application of bio-organic and organic fertilizers increased microbial activity and grape fruit quality (Li *et al.*, 2022). In this regard, these results are also consistent with Taha *et al.* (2025), who reported that a mixture of 25% compost + 75% NPK + vinasse recorded the highest potato yield.

The increase in fruit yield may be due to the integrated effect of FNPs, CF, and OF, which improved vegetative growth (leaf area and shoot length) and enhanced chlorophyll and mineral content to meet the plant's needs (Al-Waeli and Al-Janabi, 2023). These results are in agreement with many previous studies stating that the combined application of CF and OF improved the yield of many fruit species, such as grapes (Ali *et al.*, 2021; Li *et al.*, 2022).

Organic fertilizers increase available N, P, and K in the soil compared to chemical fertilizers (Wu *et al.*, 2024) and play a vital role by contributing to soil organic matter and improving soil fertility and characteristics in vineyards (Liang *et al.*, 2014; Wang *et al.*, 2017; Xie *et al.*, 2017; Yang *et al.*, 2019). Furthermore, Jaseem *et al.* (2025) recorded that the application of NPK incorporated with nano-fertilizers improved the growth, yield, and quality of grapes. Hamed *et al.* (2025) also reported an improvement in flowering, fruit set, fruit weight, and yield in olive trees treated with organic fertilization.

The combined application of 75% chemical fertilizer + 25% organic fertilizer and 75% of foliar Zn–Cu–Fe nano-fertilizer showed a positive effect on vegetative growth, leaf nutrient status, cluster traits and yield in Thompson Seedless grapevines. Such treatment can reduce 25% of use of chemical fertilizer without compromising the productivity under sandy alkaline soil condition. Future studies need to be performed to assess the long-term soil effects, nanoparticle residue dynamics, and economic feasibility. The highest overall performance of Thompson Seedless grapevines was recorded by the combined application of 75% chemical fertilizer + 25% organic fertilizer and 75% foliar Zn–Cu–Fe nano-fertilizer, which improved vegetative growth, leaf nutrient status, cluster traits and yield. Such treatment can reduce 25% of use of chemical fertilizer without compromising the productivity under sandy alkaline soil condition. Further studies should assess long term soil effects, nanoparticle residue behavior and economic feasibility.

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