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EFFECTS OF CHEMICAL AND GREEN NANO IRON AND COPPER ON GROWTH, YIELD AND FRUIT QUALITY OF CUCUMBER PLANTS (*Cucumis sativus* L).

Shahat, M. D., Abd-El-Dayem, H.M., El-Nabrawy, Amira, A. and El-Desoukey, Heba, S.
Botany Department Faculty of Agric. Benha Univ. Egypt.
E-mail: m.desouky59626@fagr.bu.edu.eg

Abstract

This study was conducted in a greenhouse at the Vegetable Research Farm of the Faculty of Agriculture at Benha University during the summers of 2023 and 2024 to study the effect of foliar spray iron and copper chemical and green nanoparticles, at different concentrations, on vegetative growth and the yield parameters of cucumber fruits (hybrid variety 'Viva Sun'). The results obtained showed that the foliar spraying with different applied treatments using green iron nanoparticles at 750 mg/l and green copper nanoparticles at 50 mg/l led to the highest recorded significant difference in all studied cucumber growth parameters (plant length, stem diameter, number of branches, number of leaves, leaf area, fresh weight, and dry weight); yield parameters (total yield per plant, total yield per treatment, number of fruits per plant, number of fruits per treatment, and fresh and dry weight); fruit quality (fruit length, fruit diameter, firmness, and total soluble solids); and photosynthetic pigments (chlorophyll a, chlorophyll b, total chlorophyll (a + b), and carotenoids). This increase in all the above-mentioned traits of growth and fruit yield parameters compared to the control treatment and other treatments was observed after 45 and 65 days of cultivation during both seasons. It can be concluded that the foliar application treatments of green nano-iron at 750 mg/l and green nano-copper at 50 mg/l have improved the growth, productivity, and quality of cucumber plants and were the most effective treatments that can be used as an alternative to chemical nano-nutrients.

Keywords: *Chemical Nano nutrients – Green Nano nutrients – Cucumber - Nano iron Nano copper*

1. Introduction

The cucumber (Cucumis sativus L.), one of the most significant vegetable crops in the Cucurbitaceae family, is regarded as one of the oldest vegetables to be grown, having been grown for more than 5,000 years (**Wehner and Guner, 2004**). Because of its substantial nutritional value, low-calorie level, and high water content, it is consumed in large quantities. After cabbage, tomato, and onion, cucumbers are the fourth most eaten vegetable in the world **(Crosby, 2008)**. Cucumber fruits have a number of bioactive substances that support human health in addition to their nutritional value, including flavonoids, antioxidants, vitamins, and vital minerals (**Maheshwari *et al.*, 2014**).

Being a thermophilic and frost-sensitive crop, cucumbers need particular climatic factors to grow and produce at their best, such as ideal temperatures, light levels, humidity, and nutrient availability. According to (**El-Aidy *et al.*, 2007**), protected production systems, especially greenhouses, offer advantageous microclimatic conditions that improve fruit quality, productivity, and vegetative growth all year round. Therefore, one of the key goals of contemporary vegetable production is to increase cucumber output and fruit quality in greenhouse settings.

Nanotechnology has recently drawn more interest in agricultural research as a potentially useful instrument for raising crop yields and optimising nutrient use. Nanofertilisers, in contrast to conventional fertilisers, are characterised by their diminutive particle size (1–100 nm), extensive surface area, and enhanced reactivity, facilitating superior nutrient absorption, transport, and utilisation within plant tissues **(Avila-Quezada *et al.*, 2022)**. Furthermore, nano-fertilisers save the environment, minimise nutrient losses, and promote sustainable farming methods.

Green-synthesised nanoparticles are a more sustainable option than chemically produced nanomaterials. Instead of employing hazardous chemicals during synthesis, green nano-fertilisers are made using biological agents or plant extracts as reducing and stabilising materials. Due to their affordability, environmental safety, and compatibility with sustainable agriculture, these green methods are especially well-suited for application in protected agricultural systems (**Bansal *et al.*, 2025**)

Essential micronutrients like iron (Fe) and copper (Cu) are vital to plant physiological and biochemical activities. Iron is an essential ingredient of many metalloproteins and enzymes found in mitochondria and chloroplasts, and it plays a crucial role in respiration, photosynthesis, electron transport networks, and chlorophyll formation. (**Kirby and Mengele 1987; Marschner, 1995)**

Copper has a role in the formation of lignin, antioxidant defence systems, photosynthetic and respiratory electron transport chains, and the activation of many enzymes. Both elements are necessary in trace levels, but too much of them can cause oxidative stress and metabolic problems, while too little of them restricts plant growth and production (**Bennett, 1945; Mitchell 1961**).

Applying iron and copper in nano-form, whether chemically or by green synthesis, may increase their bioavailability, improve the nutritional status of plants, and favourably affect the development, production, and fruit quality of cucumber plants grown in greenhouses. Therefore, it is crucial to assess how chemical and green nano-forms of iron and copper affect the development and physiological function of cucumbers in order to design sustainable fertilisation techniques.

2. Materials and methods

Experiment design:

During the summers of 2023 and 2024, a field experiment was conducted in a plastic greenhouse at the Vegetable Research Farm of the Faculty of Agriculture, Benha University, to study the effects of different foliar spray sources of green nanoparticles and iron and copper chemicals at varying concentrations on vegetative growth and fruit set in cucumbers. On June 1st of the first season and June 5th of the second season, seeds of the 'Viva Sun' hybrid cucumber variety were sown in 84-cell germination trays. 50 days after sowing in the trays, the seedlings were transplanted into the greenhouse. All recommendations of the Ministry of Agriculture regarding fertilization, irrigation, and disease and pest control were followed. The plants were treated four times and trained on supports for vertical growth. Twenty days after transplanting from the nursery, the first spraying was applied, with each subsequent spraying occurring 15 days' intervals.

The Vivasen hybrid has excellent yield, indeterminate development, hermaphrodite, parthenogenesis, resistance to fungal diseases such powdery mildew and downy mildew, fruit that is 15–17 cm long, and a dark green colour.

The growing medium is made up of peat and vermiculite (1:1 volume to volume), along with fungicides (50 g Topsin), macronutrients (250 g ammonium nitrate, 200 g superphosphate, 100 g potassium sulphate, and 25 g magnesium sulphate per 50 kg), and 3 kg calcium carbonate to balance the pH (**Smith, 1971).**

The greenhouse was divided into fifteen rows, each 15 metres long and one metre wide. Seedlings were planted in the centre of each row, spaced 30 cm apart. Fifteen-day-old cucumber seedlings with three true leaves were grown in the greenhouse. Natural light conditions were used for cucumber cultivation, with daily temperatures ranging from 25 to 38°C and a constant relative humidity of 75%. The Egyptian Ministry of Agriculture's guidelines for cultivation techniques were followed, including fertilization, drip irrigation, and disease and pest control. The plants were drip-irrigated twice weekly during the growing season to maintain soil moisture at 60%. The main stem was trained by tying each plant to a vertical polyethene string suspended from a horizontal support wire five metres above the rows to guide vertical growth. Cucumbers were harvested twice weekly, and the number, weight, and quantity of fruit were recorded each time. The fruit was commercially mature, measuring 10–15 cm in length at harvest.

Three replicates of each treatment, each containing 10 plants, were used in a completely randomized block design experiment.

The experiment in each season included thirteen treatments as follows: Control (plants were sprayed with distilled water), Chemical nanoparticles Fe (250, 500 and 750 mg/l), Green nanoparticles Fe (250, 500 and 750 mg/l). Chemical nanoparticles Cu (50,75 and 100 mg/l). Green nanoparticles Cu (50,75 and 100 mg/l).

Preparation of the nanoparticles: Chemical and Green Synthesis of Iron and Copper Nanoparticles

Chemical synthesis of Iron nanoparticles

Iron nanoparticles were synthesized using ammonium hydroxide **(Fekry *et al.*, 2021)** as a reducing agent for $FeCl_3$ and $FeSO_4$ (2:1 w/w) in a final ratio of 1:5 (v/v), and the mixture was stirred until a black sediment formed **(Darwesh *et al.*, 2019).**

Chemical synthesis of copper oxide nanoparticles

The aqueous solution of $CuCl_2 . 2H_2O$ (0.2 M) was prepared in a clean round-bottom flask. One ml of glacial acetic acid was added to the above aqueous solution and heated to 100 °C with constant stirring. 8 M NaOH was added to the above heated solution until the pH reached 7. The colour of the solution changed from green to black immediately, and a large amount of black precipitate formed. The precipitate was centrifuged and washed 3- 4 times with deionized water. The obtained precipitate was dried in air for 24 hours. This powder was further used for the characterization of CuO nanoparticles **(Eltoum *et al.*, 2020).**

Biosynthesis of Copper Oxide Nanoparticles

For the biosynthesis of copper oxide nanoparticles, a volume of 50 mL of olive oil water extract was transferred into 100 mL Erlenmeyer flasks, and the pH was adjusted to 7.0. Then, 0.5 mL of a stock solution (100 mM) of copper salt, $CuSO_4$, was added to obtain a final concentration of 5 mM. The flasks were incubated for 1 day on an orbital shaker (100 rpm) at 25°C in the dark. Erlenmeyer flasks containing only the olive oil water extract or the solution of $CuSO_4$ were established as controls. All the assays were performed in triplicate. The formation of copper oxide nanoparticles was detected **(Darwesh *et al*., 2023).**

Biosynthesis of Iron Oxide Nanoparticles

For the biosynthesis of iron oxide nanoparticles, a volume of 50 mL of olive oil water extracted was transferred into 100 mL Erlenmeyer flasks, and the pH was adjusted to 7.0. Then, 0.5 mL of a stock solution (100 mM) of iron salt, FeSO4, was added to obtain a final concentration of 5 mM. The flasks were incubated for 1 day on an orbital shaker (100 rpm) at 25∘C in the dark, and then the pH was adjusted to 10. Erlenmeyer flasks containing only the olive oil water extract or the solution of FeSO4 were established as controls. All of the assays were performed in triplicate. The formation of iron oxide nanoparticles was detected according to a modified method by **Elkhateeb *et al. (*2024)**.

Characterization of metal nanoparticles

The average particle size, distribution, and shape of the prepared metallic nanoparticles were investigated using a high-resolution transmission electron microscope. To load the sample into the transmission electron microscope, a drop of the

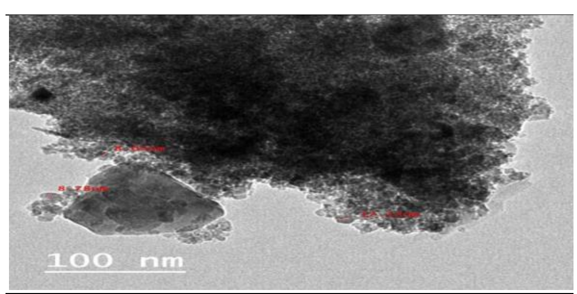

Fig 1: The particle size of Fe NPs by transmission electron microscope. The size range between (2.5 – 7.5 nm). The TEM microscope scale bar; 100nm.

well-dispersed nanoparticle solution was placed on a carbon grid with fewer than 70 holes coated with amorphous carbon, and then dried at room temperature **(Khan *et al.*, 2019).**

Managements Through Plant Growth:

During the plant's growth and development stages, the plants were sprayed four times with different specific treatments. The first time was 20 days after planting, and it was repeated every 15 days. All other agricultural practices were followed in accordance with the recommendations.

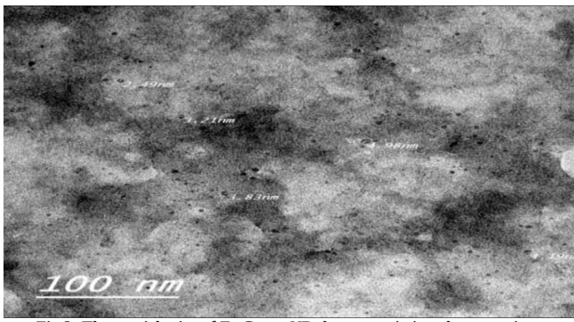

Fig 2: The particle size of Fe Green NPs by transmission electron microscope. The size range is between (8 – 12 nm). The TEM microscope scale bar: 100nm.

Sampling and collecting data:

Morphological characteristics:

Different morphological traits of the cucumber plants were measured and recorded in the two seasons. From each treatment, three plants from each treatment were randomly taken, at 45 and 65 D (days) after transplanting to the following measurement:-

Plant height (cm), Stem diameter (cm), the thickness of the plant stem was measured from the base of the stem, the middle of the stem, and the top of the stem, , total number of leaves/ plant, Leaf Area (LA), the area of the seventh leaf from the top was recorded using the (**Blanco and Folegatti** model **2005)** according to the following equation: LA = 0.88LL × LW – 4.27 - LL = Leaf Length - LW = Leaf Width, Fresh weight of stem g / plant, Fresh weight of leaves g / plant, Dry weight of stem g / plant, Dry weight of leaves g / plant

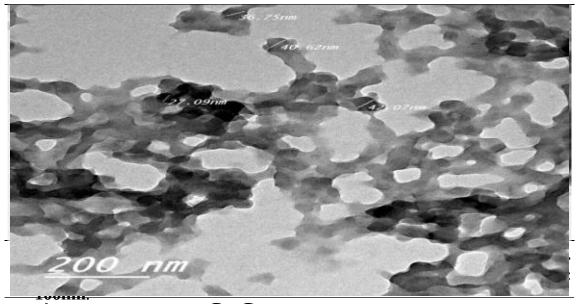

Fig 4: The particle size of Cu Green NPs by transmission electron microscope. The size range between (35 - 46 nm). The TEM microscope scale bar: 100nm.

The samples of the above ground vegetative parts were dried in each treatment, then dried in an oven at 70 ^{oC} for 48 hours till weight stability, and then the dry weight of stems and leaves was calculated.

Yield characteristics:

Data on fruit characteristics were collected when the fruit reached marketable size. ten fruits were selected from each treatment to measure the following fruit characteristics:

Yield/plant (kg), Yield (kg)/treatment, Number of fruits/plant., Number of fruits/treatment, Average fresh weight of fruit (grams) , Average dry weight of fruit (grams).

Total soluble solids (T.S.S.): was measured in the juice of cucumber fruits by using a hand refractometer according to **A. O. A.C. (1990)**.

<u>Chemical Analyses</u>

1- Photosynthetic pigments

The photosynthetic pigments (chlorophyll a., b. and carotenoids) were extracted from fresh leaf sample at 45–65 days after sowing by 80-85% acetone according to **(Wettstein, 1957)**.

2-Determination of iron and copper: -

were determined by using the atomic absorption spectrophotometer **(Perkin Elmer 3110)**.

Statistical analysis:

The data obtained in this study were subjected to statistical analysis using **Gomez-Gomez** test **(1984)**.

3. RESULTS AND DISSCUSION

Table (1) exhibits a significant increase in plant height (cm) per plant with the application of green iron nanoparticles at 750 mg/l, followed by green copper nanoparticles at 50 mg/l after 45 days and 65 days in the first and second seasons, respectively. Concerning the quantity of branches per plant, analogous results were observed; after 45 and 65 days, green iron nanoparticles at 750 mg/land green copper nanoparticles at 50 mg/l exhibited significantly elevated values in comparison to the control and other treatments. Throughout the first and second growing seasons.

All treatments exhibited a significant increase in stem diameter (cm) per plant during both growing seasons compared to the control. Green copper nanoparticles at 50 mg/l exhibited a marked enhancement relative to the control and all other treatments, followed by chemical copper nanoparticles at 50 mg/land green iron nanoparticles at 750 mg/l. This enhancement was noted during both growing seasons.

The obtained Significant effects of Fe and Cu green nanoparticles may be due to the beneficial effects of iron green nanoparticles on increasing vegetative growth, net photosynthetic rate and chlorophyll content and efficiency in treated plants. The role of green Nano Copper is a key component of several enzymes involved in redox reactions, such as polyphenol oxidase, ascorbate oxidase, and cytochrome c oxidase. These enzymes are necessary for respiration and electron transport, which directly affect energy production and metabolic activity in plant cells. Copper also plays a critical role in cell wall metabolism and lignin production. Copper is a key constituent of plastocyanin, a copper-containing protein that functions in the photosynthetic electron transport chain. Plastocyanin shuttles electrons between photosystem II and photosystem I, making copper crucial for efficient photosynthesis and carbon assimilation.

In this regard, several previous studies have shown a similar positive response in crops to iron nanoparticles, for example, **El-Desoukey *et al*., (2018)** found that during the two growing seasons, the different applied treatments led to an increase in plant length, number of leaves, leaf area (cm²), fresh weight, and dry weight after 60 and 90 days of planting on cucumber plants (*Cucumis sativus L.),* (**Singh *et al.*, 2024)** evaluated the effect of biologically synthesized iron oxide nanoparticles (Fe_3O_4 NPs) on growth. A stimulating effect on growth indicators was observed in tomatoes, unlike the control. **Yang *et al***., **(2020)** concluded that his study has a positive effect of nano-fertilizers prepared with onion extract on the growth of cucumber plants (*Cucumis melo var. flexuosus*).

Table (1): Effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on the Vegetative growth characteristics of cucumber plants grown under greenhouse conditions after 45&65 days during first and second seasons.

Treatment		Plant height(cm) /plant				Stem diameter(cm)/plant				Number of leaves /plant				Leaf area(cm)2 /plant			
Characteristic		1st		2nd		1st		2nd		1st		2nd		1st		2nd	
		45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D
Control		178.23	257.35	222.83	292.33	1.05	1.17	1.05	1.22	19.33	28.36	22.33	46.33	123.54	168.39	145.74	189.29
Fe Chemical nano	**250mg/l**	208.18	280.66	238.00	325.00	1.13	1.22	1.15	1.32	19.67	33.25	25.67	48.67	147.67	190.40	154.67	219.47
	500mg/l	210.24	284.64	233.33	331.67	1.14	1.23	1.16	1.32	23.33	34.85	25.67	51.67	159.18	189.36	163.15	227.55
	750mg/l	214.37	287.36	238.67	335.00	1.14	1.22	1.16	1.40	25.00	37.39	27.00	53.33	167.20	191.74	168.29	232.75
Fe Green nano	**250mg/l**	210.53	282.27	237.00	334.00	1.15	1.22	1.17	1.49	25.00	35.92	27.67	56.00	150.25	192.56	164.85	238.69
	500mg/l	221.49	292.38	241.33	338.67	1.15	1.23	1.17	1.47	27.33	39.57	32.67	58.00	169.20	200.13	170.70	240.35
	750mg/l	225.27	295.61	242.00	340.67	1.15	1.25	1.18	1.53	27.67	41.28	34.00	56.67	169.87	205.36	170.96	253.69
Cu Chemical nano	**50 mg/l**	190.59	276.38	230.00	324.00	1.16	1.25	1.18	1.55	22.33	29.39	24.33	49.33	137.10	186.25	157.13	229.12
	75 mg/l	187.30	275.39	210.55	324.67	1.17	1.26	1.19	1.56	20.67	30.78	24.00	50.67	142.24	189.34	155.67	231.23
	100mg/l	180.47	277.06	206.17	328.33	1.16	1.25	1.19	1.44	21.67	27.89	21.00	45.67	130.15	178.28	150.16	212.07
Cu Green nano	**50mg/l**	214.66	290.71	239.33	336.33	1.18	1.29	1.20	1.70	26.00	33.69	28.00	54.67	150.66	197.58	163.18	237.09
	75mg/l	207.13	283.41	237.67	329.67	1.18	1.26	1.20	1.67	25.11	31.54	24.67	51.33	139.63	191.45	160.98	228.64
	100mg/l	200.61	278.14	235.00	320.00	1.17	1.26	1.20	1.67	24.67	30.07	24.33	47.67	141.69	188.72	149.09	215.29
L.S.D		**8.18**	**9.81**	**7.93**	**7.37**	**0.05**	**0.08**	**0.17**	**0.16**	**4.35**	**2.64**	**4.77**	**3.72**	**10.48**	**6.27**	**6.27**	**7.46**

Data in **Table (2)** shows the effect of nano-treatments on fresh stem weight (g/plant). Regarding fresh stem weight (g/plant), all nano-nutrient treatments resulted in a significant increase in stem mass after 45 and 65 days of planting in both growing seasons. The application of green nano-iron at 750 mg/l resulted in the highest fresh stem weight after 45 and 65 days in the first and second seasons. Among the copper treatments, green copper nanoparticles at 50 mg/l ranked first after 45 and 65 days in the first and second seasons. A similar upward trend was observed in fresh leaf weight. Treatments with green iron nanoparticles, particularly at 750 mg/l, resulted in the highest values on both sampling dates for both seasons. Green copper nanoparticles at 50 mg/l achieved the highest values among copper applications in the first and second seasons. Higher concentrations showed relatively weaker responses.

The dry weight of the stem and leaves exhibited a pattern consistent with that of the fresh biomass of the stem and leaves. Green iron nanoparticles at 750 mg/l produced the highest stem dry weight values in both seasons relative to the control. Chemical treatments utilizing nanoparticles demonstrated moderate enhancement, whereas formulations of green nanoparticles exhibited markedly superior increases, particularly green copper nanoparticles at a concentration of 50 mg/l.

Our results are in agreement with **El-Desoukey *et al*., (2018)**, who reported that the results showed that during the two growing seasons, the different treatments applied led to an increase in leaf area (cm²), fresh weight, and dry weight after 60 and 90 days of planting. Also (**Wehner and Guner, 2004**). indicated that various concentrations of nanoparticles Exposure to Fe_2O_4 NPs caused an increase in the fresh weight content of cucumber plants, **Yang *et al***., **(2020)** showed that The addition of iron oxide nanoparticles (nFe_2O_3) and iron oxide nanoparticles (nFe_2O_3) significantly improved plant biomass on soybean plants , **Murgueitio-Herrera *et al.*, (2022)** indicated that the FeO NPs indicate, at a concentration of 270 ppm, increases of 10.3% in root size, 55.1% in dry biomass, and 25.6% in leaf area.in cabbage, **Shah *et al.*, (2023)** reported that a dose-proportional inhibition of biomass in watermelon seedlings treated with CuO nanoparticles at concentrations of 75, 150, and 225 mg/l.

Similar results were previously mentioned despite the generally reported inhibitory effects of copper oxide nanoparticles on plant biomass, the magnitude and direction of the response appear to be highly dependent on nanoparticle concentration and plant species. In this context, **Nair and Chung (2015)** and **Mosa *et al.*, (2018)** consistently reported a significant reduction in cucumber biomass, with the latter demonstrating a clear concentration-dependent inhibitory trend. Conversely, (**Wehner and Guner, 2004**). observed a stimulatory effect on cucumber fresh weight at low concentrations of copper oxide nanoparticles, suggesting a hermetic response at sub-toxic levels. Similarly, **Nair and Chung (2015)** confirmed that higher concentrations of copper oxide nanoparticles exert strong phytotoxic effects, as evidenced by significant growth inhibition and dose-dependent biomass reduction in watermelon seedlings.

In this context, several previous studies have demonstrated a similar positive response in crops to iron nanoparticles. For example, a study by **Shah *et al.*, (2023)** on cabbage showed an improvement in plant biomass after the application of iron oxide nanoparticles. Furthermore, the results of **Yang *et al***., **(2020)** highlight the effect of iron oxide nanoparticles when used with plant extracts, as these nanoparticles enhanced cucumber growth and fresh biomass.

Table (2) Effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on the fresh and dry weights of cucumber plants stems and leaves grown under greenhouse conditions after 45&65 days during first and second seasons .

Treatment / Characteristic		Fresh weight of stem (g) / Plant				Fresh weight of leaves (g) / Plant				Dry weight of stem (g) / Plant				Dry weight of leaves (g) / Plant			
		1st		2nd		1st		2nd		1st		2nd		1st		2nd	
		45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D	45 D	65 D
Control		141.24	181.04	173.50	267.33	69.18	203.77	71.21	282.79	13.02	19.88	16.68	26.70	4.29	15.32	6.96	20.57
Fe Chemical nano	250 mg/l	202.14	242.50	239.00	343.50	94.10	242.55	108.58	324.68	20.21	32.09	25.53	44.06	8.19	17.01	9.83	28.32
	500 mg/l	198.13	231.45	237.17	377.33	97.19	245.79	117.66	363.27	18.09	28.01	22.91	45.17	9.11	17.25	10.82	30.08
	750mg/l	219.24	241.56	236.36	378.33	105.17	253.01	127.18	366.95	23.43	27.89	22.01	48.04	9.31	17.85	11.01	30.12
Fe Green nano	250 mg/l	215.17	263.15	250.00	388.00	99.76	260.76	129.05	369.11	22.43	33.22	29.23	48.18	9.17	18.24	11.40	35.24
	500 mg/l	223.30	274.58	252.67	391.00	107.01	267.39	138.47	398.01	25.37	36.84	31.30	52.59	9.25	18.36	13.89	37.47
	750 mg/l	234.45	289.13	249.83	391.67	112.55	268.83	146.21	413.38	27.12	38.39	30.27	53.81	10.06	18.71	13.97	37.60
Cu Chemical nano	50mg/l	168.90	200.14	240.83	328.19	98.43	247.65	105.27	303.24	15.17	25.02	25.09	37.02	8.06	16.85	9.17	24.94
	75mg/l	158.30	199.38	237.83	325.22	88.52	232.64	107.22	311.56	15.02	24.36	23.97	36.69	7.07	16.47	8.06	25.33
	100 mg/l	146.16	195.99	222.16	286.99	87.60	230.40	102.15	294.99	14.24	23.78	20.27	30.18	6.29	15.66	7.67	24.42
Cu Green nano	50mg/l	216.29	254.85	250.50	371.86	103.83	254.78	137.57	330.96	23.21	32.18	30.97	48.14	9.50	17.98	12.85	29.72
	75mg/l	207.17	233.46	244.67	345.18	99.48	250.13	112.43	322.06	21.23	28.13	27.01	45.70	9.19	17.38	9.76	27.99
	100 mg/l	170.23	201.65	231.83	333.93	91.79	241.15	105.77	303.30	15.22	26.13	20.47	41.17	8.15	16.78	8.24	25.22
L.S.D		32.24	11.39	9.99	82.23	13.03	19.85	24.88	21.05	3.42	4.89	2.26	9.35	2.71	2.08	1.94	2.29

Data in **Table (3)** shows the effect of nanoparticles on yield/ plant , total yield/treatment ,number of fruits / plant , number of fruits / treatment, average fresh fruit weight (g) and fruit dry weight (g) .All characteristics were significantly affected by the application of nano nutrients .During the both seasons ,The highest yield / plant , total yield / treatment ,number of fruits / plant , number of fruits / treatment, average fresh fruit weight (g) and fruit dry weight (g)were recorded with green iron nanoparticles, particularly at 750 mg/l. These values represent significant increases compared to the control plants. In the 2nd season, productivity indicators showed a marked improvement compared to the 1st season. The highest observed yield/plant and the highest overall yield/treatment were achieved using green iron nanoparticles at 750 mg/l.

As for the copper treatments, green copper nanoparticles at 50 mg/l achieved the highest yield per plant, total yield per treatment, number of fruits per treatment, average fresh fruit weight (g), fruit dry weight (g) and number of fruits per plant 50 mg/l achieved the highest value, although their performance remained lower than that of the iron nanoparticle treatments while the remaining all treatment showed only slight increases compared to the control.

The use of nanotechnology resulted in statistically significant and sustained increases in total yield/plant, number of fruits per treatment, and fresh and dried fruit weight, compared to the control in both growing seasons. iron-based nano fertilizers, particularly green nano-iron applied at medium to high concentrations, demonstrated outstanding performance, registering the highest values for most yield indicators in both seasons. This confirms their high efficacy in enhancing crop productivity. Several previous studies, including **Rahman *et al.*, (2023)**, concluded that fertilization with nano-iron significantly increased the total fruit yield of tomatoes by 1.6 to 1.8 times compared to the control group, with chelated iron outperforming the control group. **Yang *et al***., **(2020)** also showed that the positive effect of iron oxide particles prepared from onion extract increased the yield and quality of cucumber fruits.

Although copper-based nano-treatments demonstrated considerable benefits compared to the control group, their effect was often less obvious than that of iron-based treatments. However, selected concentrations of green copper nanoparticles consistently represented the most effective treatments within the copper for all evaluated crop traits. The observed cumulative improvement in crop components with nano-applications reflects enhanced plant growth and fruit development across both growing seasons. Further supporting evidence for these findings was found in a study by **Zhao *et al***., **(2021)**, who reported that lower concentrations of copper nanoparticles increased tomato yield by 10.7% and 6.5%, respectively, compared to the control. Consistent with these results, **Hernández-Hernández *et al***., **(2021)** observed that higher concentrations of copper nanoparticles (7.2 and 9.0 mg/l) produced the greatest fruit weight and diameter in watermelons. Similarly, **Batool *et al***., **(2022)** showed that the optimal concentration of copper nanoparticles (20 mg/l) increases the number of fruits and the yield of sweet peppers, while higher concentrations lead to decreased yield. Furthermore, a study by **Olivarez-Rodríguez *et al***., **(2024)**. demonstrated that spraying copper on tomato leaves significantly improved tomato yield, achieving a 66% increase compared to untreated plants.

Table (3) Effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on total yield of cucumber grown under greenhouse conditions after 45&65 days during first and second seasons .

Characteristics	Treatment	Yield / plant (kg)		Total Yield / Treatment (kg)		Number of fruits /plant		Number of fruits / Treatment		Average fresh weight fruit (g)		Average Dry weight fruit (g)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Control		2.51	3.72	25.07	37.16	35.29	42.48	352.90	424.80	71.03	87.47	3.39	3.53
Fe Chemical nano	250 mg/l	3.54	5.08	35.42	50.79	37.23	52.10	372.30	521.00	95.13	97.48	4.92	4.99
	500 mg/l	3.67	6.25	36.68	62.54	37.57	62.83	375.70	628.30	97.62	99.54	4.80	5.36
	750 mg/l	3.63	6.88	36.32	68.75	37.11	69.00	371.10	690.00	97.88	99.64	5.01	5.43
Fe Green nano	250 mg/l	3.83	5.95	38.25	59.48	39.15	60.33	391.50	603.30	97.71	98.59	4.77	5.47
	500mg/l	4.00	7.40	39.99	73.95	40.46	72.79	404.60	727.90	98.85	101.60	5.26	5.71
	750mg/l	4.05	8.06	40.50	80.58	40.66	78.00	406.60	780.00	99.60	103.30	5.46	5.57
Cu Chemical nano	50 mg/l	3.49	4.18	34.90	41.82	36.38	45.18	363.80	451.80	95.93	92.56	4.85	4.43
	75 mg/l	3.46	4.71	34.61	47.07	36.54	52.00	365.40	520.00	94.71	90.52	4.30	4.40
	100 mg/l	3.17	5.65	31.72	56.50	35.22	62.47	352.20	624.70	90.06	90.44	4.43	4.82
Cu Green nano	50 mg/l	3.62	6.97	36.23	69.69	37.33	70.09	370.80	700.90	97.72	99.43	5.07	5.26
	75 mg/l	3.59	6.14	35.94	61.39	37.20	63.94	372.00	639.40	96.61	96.01	4.40	4.92
	100 mg/l	3.57	4.86	35.66	48.62	37.08	52.29	373.30	522.90	95.52	92.99	4.87	4.87
L.S.D		**1.65**	**1.91**	**5.54**	**3.77**	**3.29**	**10.11**	**30.63**	**37.18**	**6.89**	**7.81**	**1.31**	**1.29**

Data in the **Table (4)**indicated that the significant effect of nano-nutrient treatments on fruit length during the both seasons. A significant increase in fruit length was observed in all nano-treatments compared to the control. The highest fruit length (was recorded with the use of green iron nanoparticles at 750 mg/l. Among the copper treatments, green cupper nanoparticles at 50 mg/l resulted in the longest fruit length in the 1st and 2nd seasons.

Fruit diameter showed a significant increase with nano nutrient treatment compared to the control. The highest fruit diameter values were recorded with green iron nanoparticles at 750 mg/l. For copper treatments, green copper nanoparticles at 50 mg/l achieved the highest values in 1st and 2nd seasons.

Fruit firmness & T.S.S increased significantly with the use of nano-fertilisers compared to the control. During the both seasons, green iron nanoparticles at 750 mg/l recorded the highest firmness value, followed by green copper nanoparticles at 50 mg/l showed superior firmness & T.S.S compared to other copper concentrations.

These previous studies confirm the effectiveness of iron-based nano-nutrient in improving the yield and quality of various vegetable crops. **Guillén-Enríquez *et al*.**, **(2022)** found that foliar application with iron oxide nanoparticles greatly increased cucumber fruit output and quality, comprising fruit size, diameter of the fruit, and bioactive component synthesis **Demarchi *et al*.**, **(2019)** demonstrated the superiority of nano- iron treatments in increasing the number, weight, yield, and overall firmness of cucumbers. Similarly, **Rahman *et al*.**, **(2023)** observed a significant improvement in tomato fruit quality when using iron treatments compared to conventional fertilisation, highlighting the broad agricultural potential of iron nano-applications.

In this context, several previous studies have demonstrated a similar positive response to copper nanoparticles in crops. Collectively, these studies highlight the positive role of metal nanoparticles in improving the yield and quality of horticultural crops. **Zhao *et al*.**, **(2021)** reported that low concentrations of copper nanoparticles significantly improved tomato yield, as evidenced by increases in individual fruit weight (10.2% and 7.5%, respectively) and total yield (10.7% and 6.5%, respectively) compared to the control. Similarly, **Bansal *et al*.**, **(2025)** observed that foliar spraying with copper nanoparticles significantly increases the physical and nutritional characteristics of watermelon fruits, with the highest concentrations of copper nanoparticles (7.2 and 9.0 mg/l) producing the largest fruit weights and diameters. This consistency across different crops suggests that copper nanoparticles can effectively stimulate fruit growth, although the magnitude of the response appears to be concentration- and crop-type-dependent.

Table (4) Effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on fruits characteristics of cucumber grown under greenhouse conditions after 45&65 days during first and second seasons.

Treatment	Characteristics	Fruit length (cm)		Fruit diameter(cm)		Fruit firmness (g/cm2)		TSS (%)	
		1st	**2nd**	**1st**	**2nd**	**1st**	**2nd**	**1st**	**2nd**
Control		14.87	14.54	2.08	3.01	218.39	244.33	3.20	4.11
Fe Chemical nano	250 mg/l	15.56	16.90	3.37	3. 45	245.88	278.00	4.90	5.10
	500 mg/l	15.86	16.57	3.35	3. 49	253.35	288.67	4.97	5.53
	750 mg/l	16.39	16.97	3.41	3.69	247.95	288.93	5.13	5.70
Fe Green nano	250 mg/l	16.36	16.71	3.52	3.82	247.23	290.67	5.00	5.33
	500 mg/l	17.06	17.24	3.85	4.66	265.41	293.33	5.00	5.80
	750 mg/l	17.17	17.76	3.88	4. 51	269.58	293.67	5.33	5.87
Cu Chemical nano	50 mg/l	14.93	15.43	3.76	4.36	256.46	286.33	4.35	5.00
	75 mg/l	14.37	15.54	3.67	4.10	251.38	286.67	3.66	4.56
	100 mg/l	13.67	15.29	3.49	3.73	243.73	269.67	3.59	4.76
Cu Green nano	50 mg/l	16.58	17.33	3.90	4.97	262.33	293.33	4.80	5.23
	75 mg/l	15.95	16.50	3.62	4.47	259.19	288.00	4.79	5.00
	100 mg/l	15.34	16.05	3.48	3.79	250.64	281.67	4.70	4.93
L.S.D		**3.00**	**1.00**	**1.23**	**0.38**	**12.49**	**15.98**	**1.15**	**1.32**

The data in **Table (5)** demonstrate a significant impact of nano nutrient treatments on chlorophyll a, chlorophyll b, and total chlorophyll (a + b) content across 1st and 2nd growing seasons. All nano-treatments led to a substantial enhancement in the levels of chlorophyll a, chlorophyll b, and total chlorophyll (a + b) relative to control. The most significant increase was noted with green iron nanoparticles at a concentration of 750 mg/l. Green copper nanoparticles at a concentration of 50 mg/l yielded the highest concentrations of chlorophyll a, chlorophyll b, and total chlorophyll (a + b) in both growing seasons.

The carotenoid content significantly increased following nanoparticle treatment in both growing seasons. The highest concentrations of carotenoids were observed with green iron nanoparticles at 750 mg/l. Among the copper treatments, green copper nanoparticles at 50 mg/l achieved the highest carotene values compared to other copper concentrations, while higher copper levels resulted in a slight decrease in pigment accumulation during the first and second growing seasons, respectively.

The higher performance of green iron nanoparticles is ascribed to iron's important function in chlorophyll production, electron transport, and enzyme activation, consequently improving photosynthetic capability and biomass accumulation. This correlates with **Wang *et al*., (2019)** finding that, with increasing exposure time to nanoparticles, both ferric oxide (g-Fe_2O_3) and ferric oxide (Fe_3O_4) nanoparticles began to increase chlorophyll content at a certain exposure stage. Furthermore, **Gupta (2022)** observed that during the vegetative growth stage and before and after blooming, cucumber leaves were sprayed with zinc oxide (ZnNPs) and iron oxide (FeNPs) nanoparticles at concentrations of 100, 200, and 300 mg/L. The usage of both types of nanoparticles led to an increase in total chlorophyll content (15.9–17.3%), as reported by **Rahman *et al*., (2023)**. The results indicated that the relative chlorophyll concentration in tomato leaves (SPAD index) increased significantly (by 24–27%) with the administration of 10 and 20 mg/L of both nano- and chelated iron fertilization compared to the control group. **Sánchez-Portillo *et al*., (2025)** found that lettuce plants treated with iron oxide nanoparticles (Fe_3O_4 NPs) (at a concentration of 500 ppm) by irrigation showed an increase in chlorophyll and beta-carotene content ($p<0.05$). **He *et al*., (2025)** observed that in this investigation, spraying iron nanoparticles onto leaves boosted photosynthesis, with a concentration of 50 mg/L being the most effective. Furthermore, the photosynthetic rate of the leaves increased dramatically (>200%)

In this regard, multiple prior studies have indicated a similar favourable response to copper nanoparticles in crops. Collectively, these studies illustrate the favourable effect of metal nanoparticles in boosting the productivity and quality of horticulture crops **Mosa *et al.*, (2018)** indicated that CuNP caused genetic modifications in *C. sativus*. The results revealed notable adverse phenotypical changes along with decreased biomass and decreased levels of the photosynthetic pigments (chlorophyll a and b) in a concentration-dependent manner, **Wang *et al.*, (2021)** showed that the production of tomatoes using copper-based nano-agriculture was reported here in a green and biosafe manner. Cu NCs increased the activities of photosynthetic content by 19.4% at low concentrations, **Wang *et al.*, (2022)** mentioned that According to experimental findings, copper-based nanoparticles (NPs) can enhance the biomass and photosynthetic rate of Brassica plants. **Lee and Leskovar (2025)** discovered that this study assessed how CuO nanoparticles applied topically affected tomato (*Solanum lycopersicum*) seedlings. Chlorophyll fluorescence (Fv/Fm) was improved by all nanoparticle treatments.

Table (5) Effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on photosynthetic pigments in cucumber leaves grown under greenhouse conditions during first and second seasons

Treatment / Characteristics		chlorophyll a (mg/g)		chlorophyll b (mg/g)		Carotenoid (mg/g)		total chlorophyll (a + b) (mg/g)	
		1st	**2nd**	**1st**	**2nd**	**1st**	**2nd**	**1st**	**2nd**
Control		1.63	2.09	1.05	1.18	1.11	1.30	2.68	3.27
Fe Chemical nano	**250 mg/l**	2.17	2.32	1.27	1.24	1.44	1.40	3.44	3.56
	500 mg/l	2.22	2.35	1.36	1.25	1.48	1.45	3.58	3.6
	750 mg/l	2.35	2.46	1.40	1.35	1.37	1.53	3.75	3.81
Fe Green nano	**250 mg/l**	2.44	2.50	1.32	1.42	1.53	1.49	3.76	3.92
	500 mg/l	2.61	2.65	1.46	1.45	1.61	1.74	4.07	4.10
	750 ppm	2.56	2.78	1.67	1.53	1.65	1.79	4.23	4.31
Cu Chemical nano	**50 mg/l**	2.07	2.42	1.23	1.33	1.32	1.24	3.3	3.75
	75 mg/l	1.86	2.27	1.12	1.31	1.27	1.28	2.98	3.58
	100 mg/l	1.81	1.78	1.10	1.08	1.21	1.17	2.91	2.86
Cu Green nano	**50 mg/l**	2.49	2.35	1.50	1.36	1.47	1.56	3.99	3.71
	75 mg/l	2.06	2.34	1.48	1.35	1.41	1.34	3.54	3.69
	100 mg/l	1.90	2.07	1.18	1.21	1.23	1.28	3.08	3.28
L.S.D		**0.18**	**0.45**	**0.12**	**0.20**	**0.10**	**0.26**	**0.30**	**0.65**

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data in Table (6) show the effect of different nano-iron and nano-copper treatments (chemical and green) at various concentrations on nutrient content in leaves and fruits, including Fe, and Cu (mg L^{-1}).

Iron content in leaves&fruits increased markedly compared with the control. The highest values were recorded with Fe chemical nano at 750 ,500 mg/ L^{-1} and 250 mg L^{-1} followed by Fe green nano at 750 mg L^{-1} and 500 mg/ l. Moderate values were observed with Fe green nano (500 and 250 mg L^{-1}). Lower values were recorded with Cu green nano treatments. The lowest values were observed with Cu chemical nano treatments, which were lower than the control.

Copper content in leaves & fruits increased significantly compared with the control. The highest values were recorded in leaves with Cu chemical nano (100, 75 and 50 mg L^{-1}), followed by Cu green nano (100, 75 and 50 mg L^{-1}), while in fruits were recorded with Cu chemical nano (100, 75mg/l), followed by Cu green nano at 100 mg L^{-1}. Fe green nano treatments gave lower values. Fe chemical nano treatments gave the lowest readings, which were close to the control.

In this context, several previous studies have demonstrated a similar positive response in crops to iron nanoparticles. For example, **Li *et al*.**, **(2020)** observed that in their experiment, watermelon plants were treated with 100, 200, and 400 mg L^{-1} α- and γ-Fe_2O_3 nanoparticles (NPs), respectively. They discovered that the iron distribution of α- and γ-Fe_2O_3 NP treatments was closely connected to the concentrations of NPs. Both α- and γ-Fe_2O_3 NPs accumulate in the root, stem, and leaf of watermelon plants**. Sánchez-Portillo *et al*.**, **(2025)** examined the impacts of various Fe sources. Fe build-up was measured in leaf tissue. In cucumbers. No changes were detected in Fe accumulation. However, 100 mg L^{-1} of Fe_3O_4 NPs by soaking raised Fe content by 80%, while 250 mg L^{-1} compared to the control. For lettuce, large dosages of Fe_3O_4 NPs and ZnO NPs by foliar spray enhanced Fe by 26%. **He *et al*.**, **(2025)** stated that foliar application of iron nanoparticles with 50 mg l^{-1} was the most efficient concentration. Moreover, treatment raised Cabbage leaf iron content by 5.8 fold compared to the control.

Also, several previous studies have demonstrated a similar positive response in crops to copper nanoparticles. For example, **Tombuloglu *et al*.**, **(2020)** discovered that this study aims to investigate the NPs applied to barley (*Hordeum vulgare L.*) in varying concentrations (62.5, 125, 250, and 500 mg/l) for 21 days. Results showed that NPs have a spherical structure with an average.

crystallite size of 18 nm. Raising NP doses gradually increased the amount of the elements found in the composition of NPs (Cu and Fe), both in root and leaf tissues. In addition, compared with the untreated control, 500 mg L^{-1} of NP treatment increased the abundance of some macro-elements (K, Ca, Mg, and P) in roots, while the amount of these elements, except for Ca, significantly decreased in the leaves ($p < 0.05$)**. Wang *et al*.**, **(2021)** documented that the green and bio safe copper-based nano-agriculture was described for tomato production. Prepared Cu nanoclusters (NCs) showed a small size (3.0 ± 0.5 nm) and high bioavailability. At low concentration (1 mg L^{-1}), Cu NCs promoted the roots' growth in the tomato plants, especially increasing the root tip number, which might contribute to the increase in absorption of macronutrients (K, Mg and P) and micronutrients (B, Mn, Cu and Zn). Moreover, the tomato fruit qualities had improved, while the accumulation of Cu in fruits was not observed.

Table (6) The effect of foliar spraying with different concentrations and forms of iron and copper nanoparticles on the content concentration of cucumber Leaves and fruits after 65 days of transplanting in the greenhouse.

Characteristics / Treatment		Leaves		Fruit	
		Fe ppm	**Cu** ppm	**Fe** ppm	**Cu** ppm
Control		**104.10**	**10.02**	**95.32**	**8.52**
Fe Chemical nano	**250** mg L^{-1}	**263.50**	**10.11**	**205.10**	**9.13**
	500 mg L^{-1}	**290.10**	**11.64**	**220.20**	**9.64**
	750 mg L^{-1}	**301.40**	**11.42**	**234.70**	**8.66**
Fe Green nano	**250** mg L^{-1}	**189.00**	**14.48**	**161.90**	**11.82**
	500 mg L^{-1}	**214.30**	**12.29**	**170.80**	**10.46**
	750 mg L^{-1}	**218.20**	**11.79**	**185.80**	**9.95**
Cu Chemical nano	**50** mg L^{-1}	**98.20**	**32.20**	**90.20**	**22.90**
	75 mg L^{-1}	**88.40**	**36.50**	**77..10**	**25.50**
	100 mg L^{-1}	**87.80**	**39.80**	**68.50**	**27.20**
Cu Green nano	**50** mg L^{-1}	**124.10**	**23.54**	**100.10**	**17.54**
	75 mg L^{-1}	**106.70**	**28.00**	**94.30**	**21.12**
	100 mg L^{-1}	**113.20**	**31.10**	**79.20**	**23.80**
L.S.D		**53.02**	**4.67**	**30.73**	**4.09**

Conclusion:

The present study unequivocally revealed that the foliar application of green synthesized nano-iron and nano-copper markedly enhanced the growth, productivity, and physiological performance of cucumber plants cultivated in greenhouse conditions. The application of green nano iron at 750 mg/l and green nano copper at 50 mg/l emerged as the most effective treatment among all those tested. This treatment led to significant improvements in vegetative growth and fruiting characteristics, as well as a notable enhancement in the quality attributes of the fruit. This treatment significantly enhanced photosynthetic pigments, such as chlorophyll a, chlorophyll b, and carotenoids, indicating a general improvement in photosynthetic efficiency and plant health. Applying green nano iron at 750 mg/l and green nano copper at 50 mg/l as a foliar spray on cucumber plants in a greenhouse is advised based on the results. To attain ideal growth, yield, and quality, the first spraying should be done 20 days after transplanting and then repeated at 15-day intervals for a total of four sprays.

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