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Article

Tomato production under protected conditions with foliar applications of metal nanoparticles

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Abstract

Tomato (*Solanum lycopersicum*, L.) is the most important vegetable in the world in terms of production volumes, which will have to continue to increase to meet future consumption needs. In this regard, the use of nanotechnology could make the supply of nutrients to plants more efficient and improve and increase agricultural production. The objective of the study was to determine the effect of foliar application of Zn, Cu, and Fe nanoparticles on tomato production and quality. In 2021, a Roma-type tomato crop was established under protected agriculture. The treatments consisted of the individual and combined foliar application of nanoparticles of Zn, Fe, Cu, Zn+Fe, Zn+Cu, Fe +Cu, Zn+Fe+Cu, plus a control without application. It was found that the individual application of the nanoparticles did not improve tomato production, however, the combined supply increased the yield. The highest production was recorded with Zu+Fe+Cu, which was 66% higher than the control plants, with this treatment the lycopene content also doubled (2.23 mg g^{-1} dry matter). The nanoparticles increased the nutrient content within the maximum limit allowed for consumption. Therefore, the application of micronutrient nanoparticles supplied in combination is a viable alternative to improve tomato yield and quality.

Keywords:

Solanum lycopersicum, nutritional content, lycopene content.

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Introduction

Tomato fruits are an integral part of the diet of people around the world, they are characterized by being an important source of vitamin C, potassium, folic acid, flavonoids, among other elements (Perveen *et al*., 2015). Tomato consumption is constantly growing, but the slowdown in yield growth due to limited natural resources, such as soil, water, and soil fertility, may result in not producing the amount needed to meet the demand of the population, which will continue to grow (FAO, 2017).

Likewise, the indiscriminate use of mineral fertilizers has contributed to the increase in yield, but it has also led to the emission of greenhouse gases, eutrophication of water, acidification of water bodies, increase in soil salinity, and loss of biodiversity of soil microorganisms (Skowroñska and Filipek, 2014).

According to the trends and challenges of food and agriculture, it is necessary to look for environmentally friendly alternatives, innovations that allow food production to continue increasing according to future demand (FAO, 2017). In this sense, nanotechnology is considered to be the fifth revolutionary technology of the century after biotechnology, which researches, manipulates, characterizes, and uses particles with sizes between 1 and 100 nm, which are currently showing utility in medicine, biology, chemistry, physics, materials sciences, the environment, and agriculture (Chhipa, 2017).

Currently, there are nanoparticles of Ag, Si, Ti, Mn, Mo, Cu, Zn, and Fe, formulated as oxides (Chhipa, 2017). Of these chemical elements, some are essential in plant nutrition (Zulfiqar *et al*., 2019). In areas destined for vegetable cultivation, in most cases, there are soils deficient in Zn, Cu, and Fe (Liu and Lal, 2015). Commonly, these micronutrients are added in low proportions to N, P, and K fertilizers, but their availability is limited. The application of micronutrients in the form of nanoparticles could increase their efficiency to improve agricultural yields and additionally act as fortification products in human food (Liu and Lal, 2015).

Nanoparticles have the ability to enter the plant when applied to leaves or to the soil, due to their small size (< 100 nm), they have greater surface area and reactivity (Zulfiqar *et al*., 2019). They also show high solubility (Morales-Díaz *et al*., 2017), adsorption, and availability for the plant; losses are reduced and efficiency in their use increases (Zulfiqar *et al*., 2019).

On some occasions, at high doses (>100 ppm) the application of these products generates negative effects on the accumulation of biomass (Liu and Lal, 2015; Seleiman *et al*., 2020). Therefore, it is necessary to evaluate application at low doses to avoid phytotoxicity problems (Hafeez *et al*., 2013; Van-Nguyen *et al*., 2022). It is also possible to potentiate the effect of metal nanoparticles if they are supplied in combination (Zulfiqar *et al*., 2019).

In tomato, there are few studies on the application of nanoparticles at low and combined doses of metal nanoparticles and the elemental content in the fruit, so the objective of this research was to determine the effect of the foliar application of nanoparticles of Zn, Cu, and Fe, administered individually and in combination, on tomato production, nutritional content, and production quality.

Materials and methods

Experiment location

The study was conducted at the Faculty of Agricultural Sciences of the Michoacán University of San Nicolás de Hidalgo in Apatzingán, Michoacán, Mexico; it is located at 19° 04’ 56” north latitude and -102° 22’ 15” west longitude at an altitude of 325 m. The climate of the place is BSh’g, which is steppe dry and very warm (García, 2004).

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Experimental genotype

A Roma or Saladette-type tomato of determined growth, variety Primus, from the company United Genetics was used, which is early, resistant to Fusarium, with fruits with good firmness and an intense red color (Hortalizas AMBA, 2017).

Cultivation conditions, soil preparation, and transplanting

The study was carried out under protected agricultural conditions, using a 10 m x 40 m structure, with black polyethylene mesh, 30% shade and 25 x 25 threads inch^{-1} anti-aphid mesh walls. Inside this structure, a fallow and two passes of harrow were carried out. Subsequently, beds were made 1.2 m apart. Afterwards, tapes were placed and silver/black plastic mulch was installed over them.

On December 19, 2021, irrigation was applied to leave the soil at field capacity. The next day, ungrafted tomato seedlings were transplanted to the soil at plant spacing of 0.4 m and bed spacing of 1.2 m, a single row per bed.

Irrigation and fertilization

The water supply and nutrition of the tomato was carried out according to the phenological stages of the crop and the nutritional contribution of the soil and the water used for irrigation and for the preparation of the nutrient solution was considered. The following was applied by fertigation (kg ha^{-1}): 113 of N, 50 of P_2O_5, 110 (K_2O), 4 of Fe, 2 of Mn and 0.7 of B, as potassium nitrate (13N-37K_2O), urea (45N), phosphoric acid (32P), potassium phosphate (23P-24K), Tradecorp AZ® (7.5Fe + 0.65B + 3.5Mn), and TRADEBOR® (15.4 B).

Fertigation was administered twice a week at electrical conductivity (EC, dS m^{-1}) EC= 1 (vegetative stage), EC= 1.5 to 2 (flowering to the beginning of fruiting) and 2 to 2.5 (fruiting start to harvest). The nutrient solution was injected at a pH of 6, which was reached with the addition of 85% phosphoric acid. The fertilizers were weighed on an Electronic Kitchen Scale portable scale, model SF-400.

Treatments and experimental design

The treatments consisted of the foliar application of nanoparticles (NPs) formulated as ZnO, Fe_2O_3 and CuO, administered individually and in combination: Zn, Fe, Cu, Zn+Cu, Zn+Fe, Cu+Fe, Zn+Cu +Fe and a control without application, totaling eight treatments. The application concentration was 10 ppm of active ingredient from each nanoparticle.

The treatments were distributed in a randomized complete block experimental design with four repetitions, generating 32 experimental units. The ZnO used had a concentration of 79.7% and a particle size of 67 nm. Fe_2O_3 at the concentration of 69.3%, with a particle size of 27 nm. For its part, CuO was at the concentration of 78.8% and with a particle size of 40 nm.

The application of the treatments started 14 days after transplantation (DAT). The nanoparticles were dissolved in distilled water and Inex-A® adherent was additionally added at 1 ml L^{-1}. Applications were made in the morning to the dripping point, with manual sprays (318055 Pacto/ SWISSMEX®). The applications were made every 14 days, in total there were seven applications during the crop cycle.

Response variables

From each experimental unit, six plants were taken as a useful plot, in which the response variables were recorded. In the production stage, fruit harvests were made as they reached harvest maturity and the yield of fruits per plant (kg plant^{-1}), the number of fruits per plant, the average weight of fruits, the polar diameter, and the equatorial diameter were determined. The lycopene content of the fruits at harvest maturity was determined using the method described in Fernandez *et al*. (2007). Nutrient content was also determined in fruits according to method 2006.03 of the AOAC (2005).

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Statistical analysis

An analysis of variance was applied to the data of the response variables with the SAS statistical package, version 9.4. When the F tests were significant (p< 0.05), Tukey's mean comparison test (p≤ 0.05) was applied (SAS, 2017).

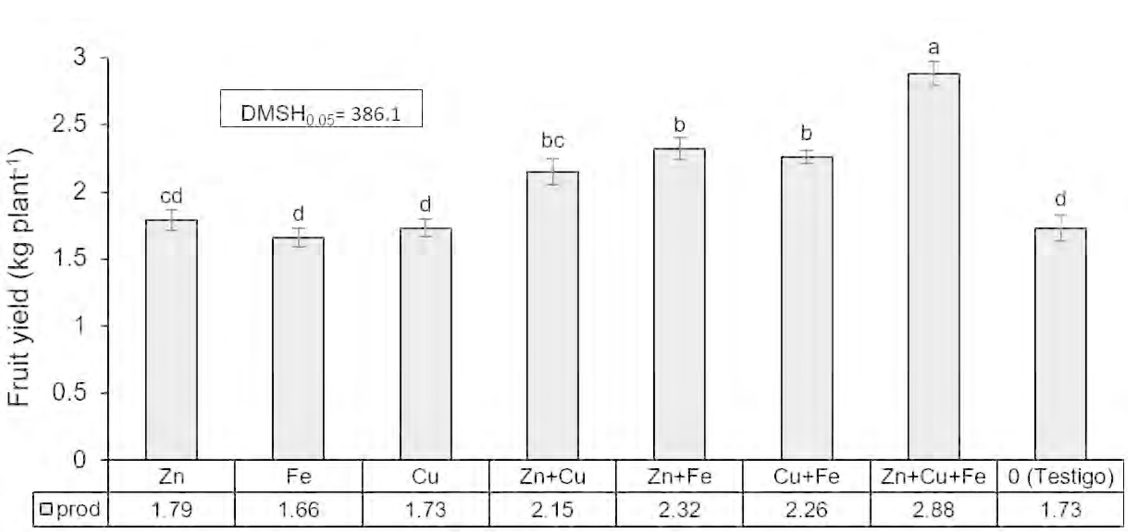
Results and discussion

Fruit yield and yield components

It was found that the individual application of the nanoparticles did not favor the increase in yield (kg plant^{-1}) compared to the plants in the control without application. Nevertheless, when supplied in combinations of two or three nanoparticles, fruit production per plant increased highly significantly (p≤ 0.01).

With the supply of Zn+Cu, Zn+Fe, and Cu+Fe, it was possible to increase yield by 24.5 to 34.3% more compared to the plants of the control without application, recording values of 2.15 to 2.32 kg plant^{-1}. On the other hand, with Zn+Cu+Fe, the plants showed the highest production, 2.88 kg plant^{-1}, which was 66% higher than the fruit yield of the plants without application (Figure 1).

Figure 1. Tomato yield as a function of foliar application of nanoparticles supplied alone and in combination. HLSD$_{0.05}$= honest least significant difference at 5% probability of error.



The increase in tomato yield with combined foliar application of nanoparticles was caused by the increase in the number of fruits per plant; in this case, it was also with the supply of Zn+Cu+Fe that the plants presented the highest number of fruits (Table 1). With any treatment, the plants produced fruits with similar average weight, equatorial diameter, and polar diameter (Table 1). No statistically significant differences (p≥ 0.05).

Table 1. Significance level and mean comparison test of the number of fruits per plant (NFP), average fruit weight (AFW), polar diameter (PD), and equatorial diameter (ED) of tomato fruits as a function of foliar application of nanoparticles.

Treatment	NFP (No. plant^{-1})	AFW (g plant^{-1})	ED (mm)	PD (mm)
Zn	26.67 de¶	66.26 a	45.96 a	53.97 a
Fe	21.75 e	60.78 a	45.07 a	53.85 a
Cu	29.17 cde	63.38 a	46.28 a	54.05 a

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Treatment	NFP (No. plant^{-1})	AFW (g plant^{-1})	ED (mm)	PD (mm)
Zn+Cu	29.67 cd	62.13 a	45.78 a	55.31 a
Zn+Fe	42 b	64.73 a	45.7 a	54.78 a
Cu+Fe	35.83 bc	55.71 a	44.66 a	51.71 a
Zn+Cu+Fe	52.17 a	65.06 a	46.57 a	56.47 a
Control	26.56 cd	65.76 a	46.27 a	56.94 a
Mean	32.98	62.48 a	45.7 8	54.64
Prob F	**	ns	ns	ns
$HLSD_{0.05}$	7.88	12.29	5.23	6.31
CV %	10.07	8.3	9.8	9.8

¶ = means with equal letters within each column do not differ statistically (Tukey, $p\leq 0.05$). **= $p\leq 0.01$; ns= not significant ($p\geq 0.05$). $HLSD_{0.05}$= honest least significant difference.

The lack of response in tomato yield and yield components with individual application of nanoparticles can be attributed to the low concentration at which they were applied (10 ppm). This differs from what was indicated by Van-Nguyen *et al*. (2022); Hafeez *et al*. (2013), who point out that plants can respond positively to the application of micronutrient nanoparticles at concentrations even below 10 ppm, as occurs in *Phoenix dactylifera*, *Zea mays*, *Cicer arietinum*, *Vigna unguiculata*, *Spinacia oleracea*, which increased their yield. On the other hand, in *Pisum sativum*, *Glycine max*, *Cucumis sativus*, *Arachis hypogaea*, among others, the positive response was achieved at concentrations greater than 10 ppm (Chhipa, 2017).

The positive response of the joint application of nanoparticles could be attributed to a cumulative effect of the functions of micronutrients in the plant, it is mentioned that these elements are important to maximize the productivity of crops. Zinc is a cofactor of several enzymes, is involved in auxin regulation, protein metabolism, and carbohydrate biosynthesis (Seleiman *et al*., 2020). Cu, on the other hand, is a constituent of regulatory proteins involved in photosynthesis and respiration and is a cofactor of antioxidants (Rai *et al*., 2018).

In the case of Fe, it is a micronutrient involved in the synthesis of chlorophyll, DNA, chloroplast structure, respiration, and various metabolic pathways (Seleiman *et al*., 2020). These functions may explain the positive response in tomato production with the combined application of these nanoparticles in the present study.

Nutritional content

Table 2, which presents the nutritional content of tomato fruits, shows that there were statistically significant differences ($p\leq 0.05$) in the content of K and Ca and highly significant differences ($p\leq 0.01$) in Fe, Zn and Cu due to the treatments. On the other hand, the content of N, P, Mg and S was not statistically modified by the treatments (Table 2).

Table 2 .Nutritional content in fresh tomato fruits as a function of the application of heavy metal nanoparticles.

Treatment	N	P	K	Ca	Mg	S	Fe	Zn	Cu
	(%)						(ppm)		
Zn	3.46 a¶	0.52 a	3.9 bc	0.06 b	0.2 a	0.23 a	63.2 cd	43.1 bc	7.88 b
Fe	3.17 a	0.46 a	3.73 c	0.08 ab	0.18 a	0.22 a	63.1 cd	45 b	4.71 e
Cu	3.23 a	0.48 a	4.15 abc	0.14 a	0.19 a	0.21 a	88.4 b	50.1 a	9.68 a
Zn+Cu	3.28 a	0.49 a	4.51 a	0.08 ab	0.2 a	0.22 a	121 a	55.4 a	5.39 de
Zn+Fe	3.33 a	0.55 a	4.36 ab	0.04 b	0.21 a	0.24 a	75.5 bc	38.2 c	6.89 d
Cu+Fe	3.32 a	0.51 a	3.81 bc	0.08 ab	0.2 a	0.23 a	57 d	39.8 bc	5.82 a
Zn+Cu +Fe	3.2 a	0.47 a	4.1 abc	0.15 a	0.18 a	0.18 a	79 b	51.6 a	9.55 a

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Treatment	N	P	K	Ca	Mg	S	Fe	Zn	Cu
			(%)					(ppm)	
Control	3.25 a	0.53 a	3.93 bc	0.1 b	0.18 a	0.23 a	58 d	40.5 bc	5.34 de
Mean	3.28	0.51	4.06	0.09	0.19	0.22	75.6	45.3	6.91
Prob F	ns	ns	*	*	ns	ns	**	**	**
$HLSD_{0.05}$	0.49	0.26	0.56	0.08	0.13	0.01	14.9	5.3	0.92
CV (%)	5.14	8.2	4.8	9.14	13.6	5.64	6.85	4.07	4.64

¶ = means with equal letters within each column do not differ statistically (Tukey, $p \leq 0.05$). *= $p \leq 0.05$, **= $p \leq 0.01$; ns= not significant ($p \geq 0.05$). $HLSD_{0.05}$= honest least significant difference.

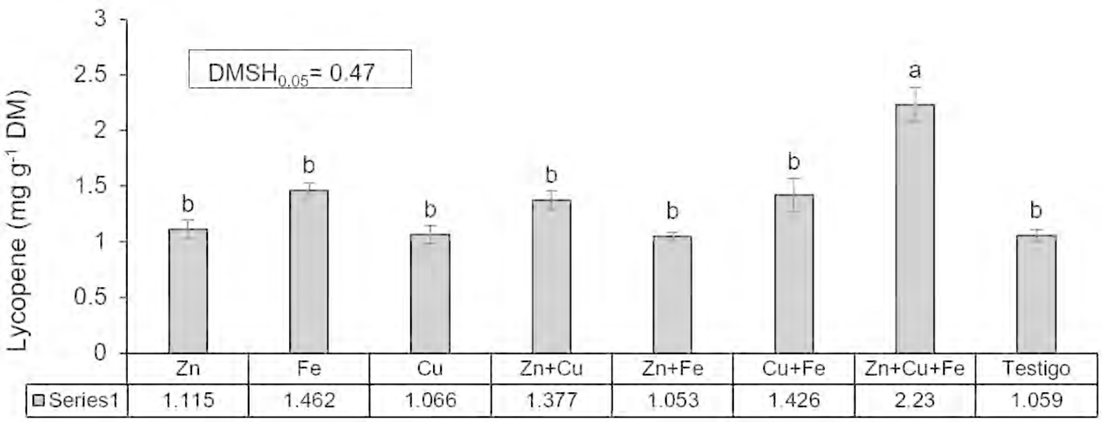
The fruits with the highest K contents were those harvested in plants with Zn+Cu, Zn+Fe, Cu, and Zn+Cu+Fe, while Ca was in higher concentrations in fruits with application of Cu and Zn+Cu+Fe. As for Fe, the content of this nutrient was favored with the treatments of Cu and Zn+Fe, although the treatment with Zn+Cu was the one that achieved the fruits with more Fe. Regarding Zn, the highest values were found in fruits harvested from plants with foliar sprays of Cu, Zn+Cu, and Zn +Cu+Fe. Finally, Cu was found to be more concentrated in plant fruits with application of Cu, Cu +Fe, and Zn+Cu+Fe NPs, with values ranging from 5.82 to 9.68 ppm (Table 2).

This indicates that the supply of NPs of Zn+Fe+Cu, in addition to being the treatment that generated the highest yield of fruits and number of fruits per plant, also had the highest nutrient content (Table 2). Despite these increases, the levels recorded in tomato fruits with any of the treatments are within the limits allowed for human consumption at any age and gender according to (NIH, 2022), making them safe and biofortified foods.

Lycopene content

Significant increases in lycopene content were recorded in the fruits of plants supplied with Zn+Cu +Fe, which represented a slightly more than twofold (105%) increase in the content compared to the fruits of the plants of the control without application (Figure 2).

Figure 2. Lycopene content in tomato as a function of foliar application of nanoparticles. $HLSD_{0.05}$= honest least significant difference at 5% probability of error.



In our study, it was possible to double the lycopene content with the joint supply of the three nanoparticles. Similar results were found by Raliya *et al*. (2015) in tomatoes, which, with application to the soil and leaves of ZnO nanoparticles at a dose of 100 ppm, recorded an increase in lycopene content of 113.1% compared to the control without application. Nonetheless, the mechanisms by which the stimulus in lycopene synthesis is induced are still unknown (Raliya *et al*., 2015).

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The response of plants to the application of nanoparticles is influenced by factors such as the nature of the particles, the interaction of the nanoparticles with the environment, and the physiological condition of the plant, as well as the age of the plant and the dose (Ahmed *et al*., 2021). Similarly, El-Raie *et al*. (2015) mention that the application of Fe NPs in tomatoes promoted the increase in lycopene; therefore, in the treatment where Zn+Cu+Fe NPs were applied, the favorable response in the increase of this compound could be partly attributed to this element since Fe has the function of activating the plant's anti-stress system and lycopene metabolization pathways.

This could have had a synergistic effect on lycopene synthesis when supplied with Zn and Cu, since all three nutrients participate in the plant's anti-stress system (Karuppanapandian *et al*., 2011). The lycopene contents in tomato fruits with most of the treatments applied in the present study are similar to those reported by Górecka *et al*. (2020), who recorded 1.18 mg g^{-1} of mature fruit dry matter in the Grandimat variety. However, it is a content lower than that recorded in the present study with the application of Zn+Cu+Fe, which indicates the advantage of this treatment to improve the functional quality of tomato fruits.

Conclusions

Individual foliar application of Zn, Fe, and Cu nanoparticles did not improve tomato production; nevertheless, the combined supply of the three minerals increased the yield and number of fruits. Zn+Fe+Cu also achieved the highest lycopene contents. The nanoparticles caused increases in the micronutrient content in tomato fruits. The levels of macro and micronutrients in fruits with the application of nanoparticles are within the limits allowed for human consumption. Therefore, the supply of Zn+Cu+Fe is recommended to improve tomato production and quality under conditions of protected agriculture with shade mesh.

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