REVISTA de la FACULTAD de AGRONOMIA

Nanoparticles that stimulate the production and quality of cucumber fruits (*Cucumis sativus* L.)

Nanopartículas que estimulan la producción y calidad de frutos de pepino (*Cucumis sativus* L.)

Nanopartículas que estimulam a produção e a qualidade de frutos de pepino (*Cucumis sativus* L.)

Juan José Reyes-Perez[1*]
Rommel Arturo Ramos-Remache[1]
Eduardo I. Jerez Mompie[2]
René Nazareno-Ortiz[3]
Kevin Patricio Murillo-Noboa[4]
José Luis García- Hernández[5]
Selenne Yuridia Márquez-Guerrero[6*]

Rev. Fac. Agron. (LUZ). 2025, 42(4): e254243
ISSN 2477-9407
DOI: https://doi.org/10.47280/RevFacAgron(LUZ).v42.n3.XIV

Crop production

Associate editor: Dr. Jorge Vilchez-Perozo
University of Zulia, Faculty of Agronomy
Bolivarian Republic of Venezuela

[1]Universidad Técnica Estatal de Quevedo. Av. Quito. km 1 ½ vía a Santo Domingo,Quevedo, Los Ríos, Ecuador.
[2]Instituto Nacional de Ciencias Agrícolas, Carretera San José-Tapaste, Km 3½, San José de Las Lajas, Mayabeque, Cuba.
[3]Universidad Técnica "Luis Vargas Torres" de Esmeraldas. Extensión San Mateo – Mutile. Nuevos Horizontes. Esmeralda, Ecuador.
[4]Universidad de las Fuerzas Armadas ESPE. Extensión Santo Domingo. Vía Santo Domingo -Vía Quevedo Km.24 Hda. Zoila Luz. Avenida Quevedo 3-703-904, Santo Domingo, Ecuador.
[5]Universidad Juárez del Estado de Durango. Ej. Venecia, Gómez Palacio, Dgo. C.P. 35000, México.
[6]Instituto Tecnológico de Torreón, Tecnológico Nacional de México. Carr. Torreón-San Pedro km 7.5, Ejido Ana. Torreón, Coahuila, CP 27170, México.

Received: 01-07-2025
Accepted: 25-08-2025
Published: 15-09-2025

Keywords:
Silicon oxide nanoparticles
Chitosan
Cucumis sativus L.
Nutraceutical quality

Abstract

Due to the high consumption of cucumber (*Cucumis sativus* L.) and its economic importance, improving resource efficiency is a priority to maximize yields. The combination of silicon oxide (SiO_2), chitosan, and micronutrients are beneficial for plant growth and development. The objective of this study was to determine the influence of micronutrient- provided SiO_2 nanoparticles encapsulated in a chitosan gel on the growth, yield, and quality of cucumber fruits. The study was conducted in a cultivation house, where three concentrations of silicon nanoparticles and a control were evaluated in a randomized block design with four replicates. Plant growth (height and stem diameter), days to flowering, number of fruits per plant, yield, and fruit quality were evaluated. Foliar application of Si-NPs promoted greater plant growth at the highest concentration (2,000 $mg.L^{-1}$), as well as improved the nutraceutical quality of cucumber fruits by increasing the contents of antioxidants, flavonoids, phenols and total soluble solids.

*Corresponding author: selenne.mg@torreon.tecnm.mx

Resumen

Debido al alto consumo de pepino (*Cucumis sativus* L.) y su relevancia económica, es prioritario mejorar la eficiencia en el uso de recursos para maximizar los rendimientos. La combinación de óxido de silicio (SiO_2), quitosano y micronutrientes, son beneficiosos para el crecimiento y desarrollo de las plantas. El objetivo del presente trabajo fue determinar la influencia de nanopartículas de SiO_2 provistas con micronutrientes, encapsuladas en un gel de quitosano, en el crecimiento, rendimiento y calidad de los frutos de pepino. Se desarrolló en casa de cultivo donde se evaluaron tres concentraciones de nanopartículas de silicio y un control, en un diseño de bloques al azar con cuatro réplicas. Se realizaron evaluaciones del crecimiento de las plantas (altura y diámetro del tallo), días transcurridos hasta la floración, número de frutos por planta, rendimiento y calidad de los frutos. La aplicación foliar de NPs-Si, permitió un mayor crecimiento de las plantas con la concentración más alta (2.000 $mg.L^{-1}$), así como mejoró la calidad nutraceútica de los frutos de pepino al incrementar los contenidos de antioxidantes, flavonoides, fenoles y sólidos solubles totales.

Palabras claves: nanopartículas de óxido de silicio, quitosano, *Cucumis sativus* L. y calidad nutraceútica.

Resumo

Devido ao alto consumo de pepino (*Cucumis sativus* L.) e sua importância econômica, é prioritário melhorar a eficiência no uso de recursos para maximizar os rendimentos. A combinação de óxido de silício (SiO_2), quitosana e micronutrientes é benéfica para o crescimento e desenvolvimento das plantas. O objetivo deste trabalho foi determinar a influência de nanopartículas de SiO_2 dopadas com micronutrientes, encapsuladas em gel de quitosana, no crescimento, produtividade e qualidade de frutos de pepino. Foi desenvolvido em casa de cultura onde foram avaliadas três concentrações de nanopartículas de silício e uma testemunha, em delineamento de blocos casualizados com quatro repetições. Foram feitas avaliações do crescimento das plantas (altura e diâmetro do caule), dias até a floração, número de frutos por planta, produtividade e qualidade dos frutos. A aplicação foliar de Si-NPs promoveu maior crescimento das plantas na maior concentração (2.000 $mg.L^{-1}$), além de melhorar a qualidade nutracêutica dos frutos de pepino, aumentando os teores de antioxidantes, flavonoides, fenóis e sólidos solúveis totais.

Palavras-chave: nanopartículas de óxido de silício, quitosana, *Cucumis sativus* L. e qualidade nutracêutica.

Introduction

The cucumber (*Cucumis sativus* L.) is a widely distributed vegetable with high demand in national and international markets, giving it considerable economic and nutritional importance (Allard *et al.*, 2020). Its yield depends on genetic material, climate and agronomic management (Erreyes *et al.*, 2023; Rivera *et al.*, 2021). Nutrient deficiencies, caused by the low availability of essential elements such as nitrogen, phosphorus, potassium, and micronutrients, affect its development and reduce productivity (Guillén *et al.*, 2022).

The use of biostimulants seeks to improve crop quality and yield, considering the soil as a living ecosystem (Paris *et al.*, 2021), while the combination of silicon oxide (SiO_2), chitosan and micronutrients has shown positive effects on plant growth. SiO_2 strengthens cell walls, while chitosan stimulates immunity and root development. Micronutrients such as iron, zinc and manganese are essential for key metabolic processes (Velásquez *et al.*, 2019). In addition, silicon nanoparticles facilitate the controlled release of nutrients (Rastogi *et al.*, 2019).

The aim of this study is to evaluate the influence of micronutrient-enriched SiO_2 nanoparticles encapsulated in chitosan gel on the growth, yield and quality of cucumber fruits.

Materials and methods

The research was conducted in the greenhouse of the 'La María' Experimental Campus located at km 7.5 of the Quevedo–Mocache road in the Mocache canton, Los Ríos province, Ecuador, at 1°04'48.6' south latitude and 79°30'04.2' west longitude, with an altitude of 75 m. The average annual temperature is 24 °C, with 84 % relative humidity and average annual precipitation of 2295 mm. The soil has a loamy texture with 32 % sand, 48 % silt and 20 % clay, with an average organic matter content of 3.9 %. Table 1 details the soil analysis carried out.

Table 1. Soil nutritional status.

	ppm		meq.100 mL^{-1}				ppm				
pH	NH_4	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn	B
6.0	11.0	27.0	0.16	10.0	0.8	20.0	5.8	6.8	216.0	5.0	0.62

A randomised block design with four treatments and four replicates was used, employing chemically synthesised silicon oxide nanoparticles (Si-NPs) at concentrations of 1,000, 1,500 and 2,000 $mg.L^{-1}$ (average diameter of 34 nm and purity of 99.9 %) applied via foliar application 12 and 25 days after transplanting (DAT) and a control treatment with distilled water only.

The Si-NPs were enriched with 0.025 % Co, 0.025 % B, 0.025 % Mo, 0.35 % Mg, 0.15 % Fe, 0.15 % Cu, 0.10 % Mn, 0.25 % Zn, 0.35 % Ca and 0.20 % S, and coated in a commercial chitosan matrix (N:P:K, 15:15:15).

The experimental unit consisted of 10 plants of the Diamante F1 cultivar, transplanted when they had three true leaves into 10-litre pots with previously characterised soil and cattle compost as substrate, in a 3:1 ratio, duly homogenised. One plant was placed per pot at a planting frame of 0.40 m between plants and 1.0 m between rows. Irrigation was programmed to meet the crop's evapotranspiration demand, using a localised drip system with a flow rate of 1.5 $L.h^{-1}$ and an estimated total irrigation depth of 175 cm for the cucumber production cycle (Rivera-Fernández *et al.*, 2021).

Staking was carried out with double wires on stakes, and weekly pruning was performed to remove old, diseased leaves or side shoots, favouring the development of the main stem.

Growth assessments

Ten plants were randomly selected per treatment and replicate to assess stem height and diameter at 45 and 60 days after sowing (DAS). Height was measured from ground level to the bud using a flexometer, while stem diameter was measured at a distance of five cm from the ground using a Mitutoyo 530 digital vernier caliper. The onset of flowering was determined when 70 % of the flowers were open.

Yield and some of its components

The number of fruits per plant in each treatment was counted and weighed, and the size of the fruits was determined by measuring their length (cm) from the apical bud to the basal bud with a flexometer and their diameter (cm) with a calibrator. Yield was estimated based on the fresh weight of fruit per plant and the number of plants possible per hectare, expressed in $t.ha^{-1}$.

Nutraceutical quality of the fruit

Five fruits per treatment and replicate were extracted to determine the variables: flavonoid content, polyphenol antioxidant capacity, and total soluble solids (TSS), as reported by Zhishen, *et al.* (1999); Henriquez, *et al.* (2002); and Singleton, *et al.* (1999).

Statistical analysis

Analysis of variance was performed to detect effects of the factors under evaluation on the dependent variables. When significant effects were detected, a Tukey test was applied at $p \leq 0.05$ using the SPSS v.24 statistical programme, and the results were plotted using the SigmaPlot v.14 programme.

Results and discussion

The plant height (figure 1) did not show a significant difference at 45 DAS, but did at 60 DAS, where a longer period of time had elapsed since the application of the biostimulant, obtaining different responses to the control.

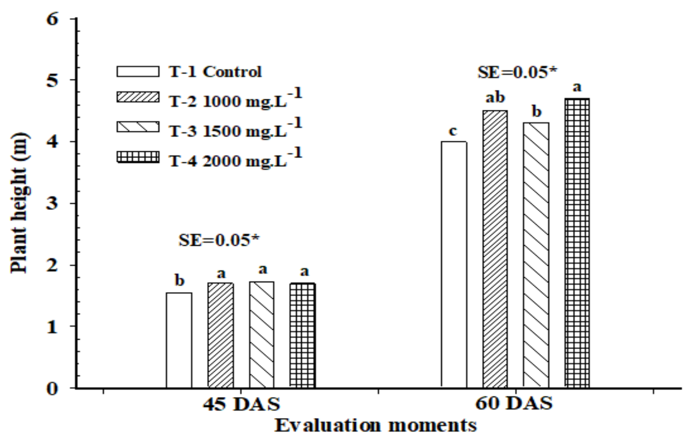

Figure 1. Plant height (m) at two points in time after sowing. Different letters above the bars indicate significant differences between treatments at $p \leq 0.05$, according to Tukey's test.

This increase in height over the control (figure 1) can be explained by the fact that Si is considered beneficial for plant growth (Yan *et al.*, 2024), acting on photosynthetic capacity, reducing the rate of transpiration, and providing greater resistance to biotic and abiotic stress, among other known actions (Canuto *et al.*, 2021).

The stem diameter (Figure 2) showed a similar behaviour to that achieved in the height growth variable, where the control treatment obtained the lowest values. However, there were no differences in Si-NPs concentrations or in DAS in the initial stages (figure 2).

The percentage increase in stem diameter, compared to the control, reached a value of 15 % in the treatment with the highest concentration, as a result of the use of silicon enriched with micronutrients and chitosan, elements that constitute a powerful stimulator of plant growth in general, as indicated by Chagas *et al.*, (2022) and Jin *et al.*,

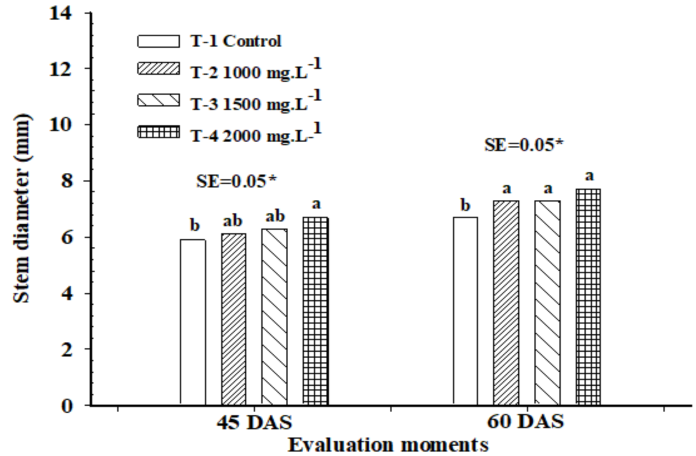

Figure 2. Stem diameter (mm) at two points after sowing. Different letters above the bars indicate significant differences between treatments at $p \leq 0.05$, according to Tukey's test.

(2024). The effect of silicon in mitigating water stress conditions in plants is well documented (Morteza *et al.*, 2020); however, the results of this study show that, under controlled conditions, silicon promotes plant growth. Furthermore, Si, in combination with Ca, Mg, Fe, Zn, and Mo, significantly improved crop development (Kovács *et al.*, 2022), resulting in taller plants with a larger diameter, among other growth variables (Reyes-Pérez *et al.*, 2024).

The biostimulants in this research did not modify the phenological behaviour of the cucumber plants, assessed based on the analysis of days from sowing to flowering (figure 3).

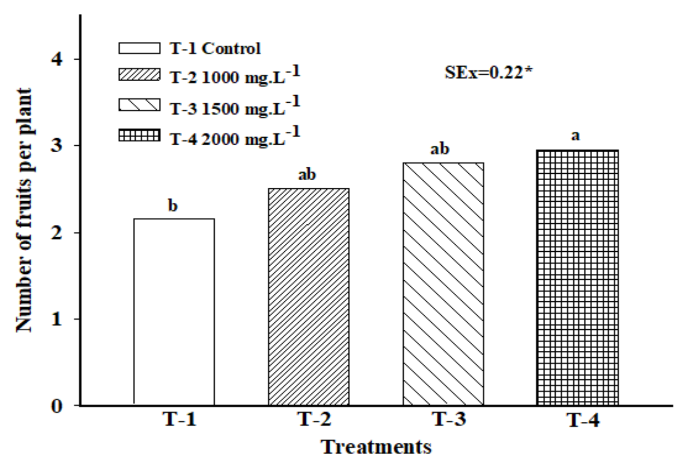

Figure 3. Time in days until flowering. Different letters above the bars indicate significant differences between treatments at $p \leq 0.05$, according to Tukey's test.

It is important to understand the phenology of cucumber plants in order to establish expert systems for agricultural problems (Laguna *et al.*, 2024), especially with the use of biostimulants.

The highest number of fruits per plant (figure 4) was obtained in the treatment with the highest concentration of Si-NPs, with an average of three fruits, with no significant differences between treatments and the control, which had an average of two fruits per plant, similar to that reported by Reyes-Perez *et al.* (2024).

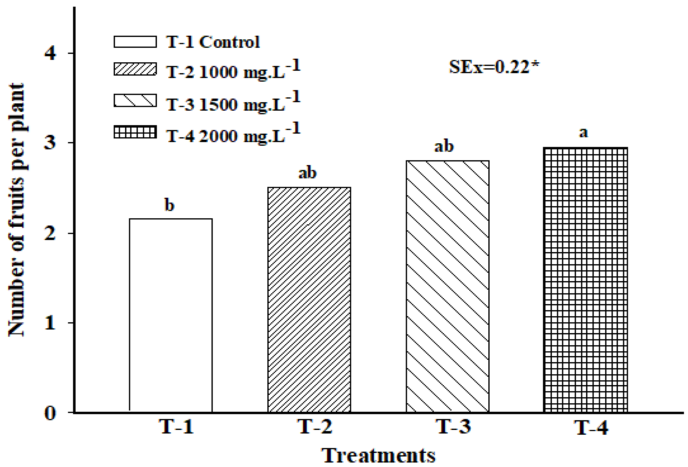

Figure 4. Number of fruits per plant at harvest. Different letters above the bars indicate significant differences between treatments at p≤0.05, according to Tukey's test.

This is related to the timing of foliar applications, as these depend on the plant species, its phenology and the required concentration (Rivera-Gutiérrez *et al.*, 2021, Galindo-Guzmán *et al.*, 2022).

Despite the importance of Zn in crop nutrition, studies on the effect of ZnO NPs on plants are limited (Tymoszuk and Wojnarowicz, 2020). However, Quirino-García *et al.* (2024) found that foliar spraying with zinc nanostructures was an alternative source of fertilisation that improved the growth and biomass production of cucumber seedlings grown in greenhouses.

When analysing the dimensions of the fruits in terms of diameter and length (figure 5), it was found that the application of Si NPs had a stimulating effect, as both variables were significantly higher than the control.

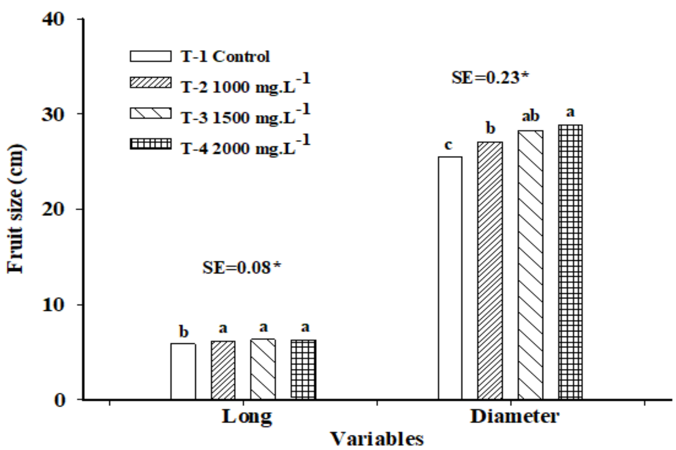

Figure 5. Fruit size (cm) evaluated by diameter and length. Different letters above the bars indicate significant differences between treatments at p≤0.05, according to Tukey's test.

As shown in figure 5, the diameter and length of the control fruits were smaller (10 and 12 % respectively) in contrast to the fruits treated with Si-NPs, results that highlight the influence of the treatments. Farouk 2023 points out that plant biostimulants have the ability to modify the physiological processes of plants, such as photosynthesis, and observed that uncoated Si-NPs, at a dose of 1000 ppm, have a negative effect on the biomass production of cucumber plants, which resulted in slower growth.

On the other hand, it has been indicated that Si NPs, due to their nanometric size, present problems of stability and dispersion (Pérez-Velasco *et al.*, 2020), which could affect their efficiency as nanofertilisers. However, this problem is reduced by using a coating or encapsulation (Kolbert *et al.*, 2022), as used in this research, where Si NPs are coated with microelements in a chitosan matrix.

Therefore, the yield results of the treatments with Si-NPs (Figure 6) showed a higher response (> 40 $t.ha^{-1}$) compared to the control (<30 $t.ha^{-1}$), although the two lowest concentrations reached similar values.

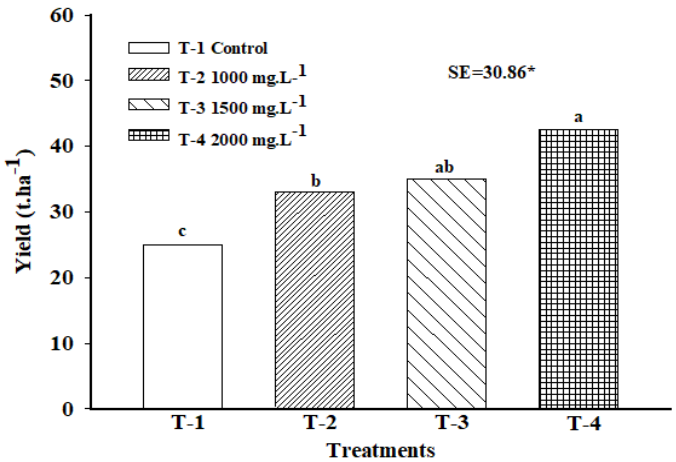

Figure 6. Yield ($t.ha^{-1}$). Different letters above the bars indicate significant differences between treatments at p≤0.05, according to Tukey's test.

The above confirms that nanoparticles have a biostimulant effect, improving the yield of cucumber plants (Ucan *et al.*, 2023). In addition, nanoparticle formulations containing chitosan result in sustainable agricultural practices (Karamchandami, *et al.*, 2024) because it is a non-toxic biodegradable biopolymer derived from chitin, which has unique properties including a large contact surface area, positive charge and biocompatibility, making them very suitable for a wide range of applications in agriculture (Saberi *et al.*, 2024).

The quality of the fruits (figure 7), evaluated based on the analysis of phytochemical variables, confirms the effect of Si NPs on their behaviour.

The highest values correspond to the treatments in which the NP-Si-based biostimulant was sprayed, compared to the control, although the lower concentrations in TSS (Figure 7D) did not show significant differences between them. The contents of the four variables were generally lower when compared to those indicated by Reyes-Pérez, *et al.*, (2024), including the control, which may have been influenced by the fact that the substrate was not similar. The increase in the amount of antioxidants, as well as the rest of the compounds evaluated, improves fruit quality, as pointed out by various authors in other crops, which in turn is the result of increases in the amount of flavonoids and polyphenols (Insanu *et al.*, 2022). In tomatoes, silicon applications increased the amount of TSS (Cázarez-Flores, *et al.*, 2023), as well as in melons (Rivera-Gutiérrez *et al.*, 2021). According to Picos *et al.*

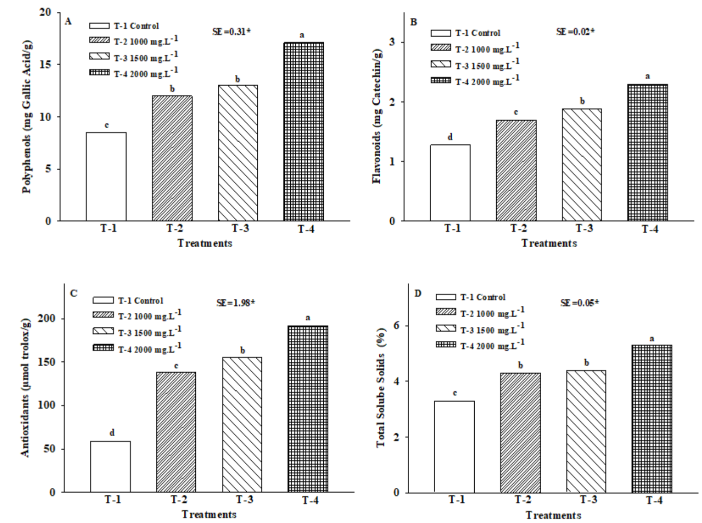

Figure 7. Nutraceutical quality of fruits, polyphenols (A), flavonoids (B), antioxidants (C) and total soluble solids (D). Different letters above the bars indicate significant differences between treatments at p≤0.05, according to Tukey's test.

(2023), chitosan treatments act as an elicitor of secondary metabolism in plants in general, while increases in phenol content are largely due to the fact that the synthesis of this compound is increased by the effect of chitosan application (Sanwam *et al.*, 2023).

In general, it has been noted that the application of nanotechnology in the agricultural sector (Tejeda-Villagómez, *et al.*, 2023) is a promising tool. This science is driving the development of a range of innovative applications and products for the benefit of agriculture, as well as its use in the production of medicinal plants (Sun *et al.*, 2023). In the case of Si NPs, these appear to be an excellent alternative for reducing the use of agrochemicals, as well as being effective systems for administering nutrients and chemical compounds to plants and crops of agricultural interest.

Furthermore, the integration of nanotechnology into agriculture represents a significant advance in improving the efficiency and sustainability of food production. This advance not only contributes to global food security, but also promotes more sustainable and environmentally friendly agricultural practices (Navarro-López *et al.*, 2025).

Conclusions

The foliar application of Si-NPs, enriched with different microelements in a chitosan gel matrix, promoted greater plant growth at the highest concentration (2,000 mg.L^{-1}) and increased the nutraceutical quality of cucumber fruits by increasing the phytochemical compounds of antioxidants, flavonoids, phenols and total soluble solids.

Literature cited

Allard, S.M., Ottesen, A.R., and Micallef, S.A. 2020. Rain induces temporary shifts in epiphytic bacterial communities of cucumber and tomato fruit. *Scientific Reports*, *10*(1), 1765. DOI: https://doi.org/10.1038/s41598-020-58671-7.

Canuto, L., Mendes, G.A., de Oliveiram, M., Araújo, J.L., Trotsk, S., Santos, M.D., Ribeiro, V.G., da Silva, J., Lopes, C., y Queiroga, F. 2021. O papel do silício nas plantas. *Research, Society and Development, 10,* 7: e3810716247. DOI: https://dx.doi.org/10.33448/rsd-v10i7.16247.

Cázarez-Flores, L.L., Angulo-Castro, A. Vega-Gutiérrez, T.A., Ayala-Tafoya, F., and Aguilar-Quiñonez, J.A. 2023. Producción de tomate en respuesta a dosis de silicio. *Ecosistemas y Recursos Agropecuarios 10*(3): e3851. DOI: 10.19136/era.a10n3.3851.

Chagas, Y., Herrera, O., y Pereira, E. 2022. Uso da quitosana na agricultura: uma revisão com ênfase na aplicação em sementes. *Research, Society and Development, 11*(2), e39911225782. DOI: https://dx.doi.org/10.33448/rsd-v11i2.25782.

Erreyes, B., Montoya, J., y Luna-Romero, E. (2023). Rendimiento del cultivo de pepino (*Cucumis sativus* L.) bajo condiciones de mulch plástico, Ecuador. *Revista Científica Agroecosistemas, 11*(1), 44-51. https://aes.ucf.edu.cu/index.php/aes/index.

Farouk S (2023). Role of biostimulants in plant's life cycle. In Biostimulants in Alleviation of Metal Toxicity in Plants (pp. 75-106). *Academic Press*. DOI: 10.1016/B978-0-323-99600-6.00010-4.

Galindo-Guzmán AP, Fortis-Hernández M, De La Rosa-Reta CV, Zermeño-González H, Galindo-Guzmán L (2022). Síntesis química de nanopartículas de óxido de zinc y su evaluación en plántulas de *Lactuca sativa*. *Revista Mexicana de Ciencias Agrícolas 13*: 299-308. https://doi.org/10.29312/remexca.v13i28.3284.

Guillén, R., Zuñiga, L., Ojeda, L., Rivas, T., Trejo, R., y Preciado, P. 2022. Efecto de la nanobiofortificación con hierro en el rendimiento y compuestos bioactivos en pepino. *Revista Mexicana de Ciencias Agrícolas, 13*(28), 173-184. https://doi.org/10.29312/remexca.v13i28.3272.

Henriquez, C., Aliaga, C., and Lissi, E. 2002. Formation and decay of the ABTS derived radical cation: A comparison of different preparation procedures. *International Journal of Chemical Kinetics 34*(12):659-665. https://doi.org/10.1002/kin.10094.

Insanu, M., Azkia-Zahra, A, Sabila, N., Silviani, V., Haniffadli, Ariranur., Rizaldy, D., and Fidrianny, I. 2022. Phytochemical and Antioxidant Profile: Cucumber Pulp and Leaves Extracts. Open Access Macedonian *Journal of Medical Sciences 10*(A):616-622..https://doi.org/10.3889/oamjms.2022.8337.

Jin, W., Li, L., He, W., and Wei, Z. 2024. Application of Silica Nanoparticles Improved the Growth, Yield, and Grain Quality of Two Salt-Tolerant Rice Varieties under Saline Irrigation. *Plants, 13*, 2452. https:// doi.org/10.3390/plants13172452.

Karamchandani, B.M., S. Dalvi, M. Bagayatkar, I.M. Banat. and S.K. Satpute. 2024. Prospective applications of chitosan and chitosan-based nanoparticles formulations in sustainable agricultural practices. Biocatalysis and Agricultural Biotechnology, 58:103210. https://doi.org/10.1016/j.bcab.2024.103210

Kolbert, Z., Szollosi, R., Rónavári, A., and Molnár, Á. 2022. Nanoforms of essential metals: from hormetic phytoeffects to agricultural potential. *Journal of Experimental Botany, 73*(6),1825-1840. https://doi.org/10.1093/jxb/erab547.

Kovács, S., Kutasy, E. and Csajbók, J. 2022. The multiple role of silicon nutrition in alleviating environmental stresses in sustainable crop production. *Plants, 11*(9), 12-23. https://doi.org/10.3390/plants11091223.

Laguna-Estrada, M., Ramírez-Pérez, N.V., Araujo-Rodríguez, J.A. y Rubín-Ramírez, N.N. 2024. Un breve resumen sobre la implementación de los sistemas expertos en problemas de agricultura. *Research in Computing Science, 153*(9), 239-245. https://rcs.cic.ipn.mx.

Morteza, S., Moharrami, F., Sarikhani, S., and Padervand, M. 2020. Selenium and silica nanostructurebased recovery of strawberry plants subjected to drought stress. *Scientifc Reports, 10*:17672. https://doi.org/10.1038/s41598-020-74273-9.

Navarro-López, N.E., González-Torres, A.M., Pérez-Pérez, A.E., Morales-Mazariego, N., y González-Moscoso, M. 2024. Nanotecnología en la agricultura: Innovación para la producción sostenible de alimentos. *Azcatl, 3*, 23-27. doi: 10.24275/AZC2024B005

Paris, L., López, H., Medina, R., y Pérez, I. 2021. Efecto de bioestimulantes sobre el crecimiento de la Vainilla Tahitensis en Daule, Ecuador. *Revista Científica Ecociencia, 8*(6), 1-14. https://doi.org/10.21855/ecociencia.86.570.

Pérez-Velasco, E.A., Betancourt-Galindo, R., Valdez-Aguilar, L.A., González-Fuentes, J.A., Puente-Urbina, B.A., Lozano-Morales, S.A., and Sánchez-Valdés, S. 2020. Effects of the morphology, surface modification and application methods of ZnO-NPs on the growth and biomass of tomato plants. *Molecules, 25*(6), 1282.DOI:10.3390/ molecules25061282.

Picos-Corrales, L. A., Morales-Burgos, A.M., Ruelas-Leyva, J.P., Crini, G., García-Armenta, E., Jimenez-Lam, S.A., Ayón-Reyna, L.E., Rocha-Alonzo, F., Calderón-Zamora, L., Osuna-Martínez, U., Calderón-Castro, A., De-Paz-Arroyo, G., and Inzunza-Camacho, L.N. 2023. Chitosan as an outstanding polysaccharide improving health-commodities of humans and environmental protection. *Polymers 15*:526 https://doi.org/10.3390/polym15030526.

Quirino-García, A., Martínez-Alonso, C., Sabino-López, J.E., Espinosa-Rodríguez, M., Vázquez-Villamar, M., y Maldonado-Peralta, M.Á. 2024. Aspersión foliar de nanoestructuras con zinc en plántulas de pepino (*Cucumis sativus* L.). *Ecosistemas y Recursos Agropecuarios IV*: e4095. DOI: 10.19136/era.a11nIV.4095.

Rastogi, A., Kumar-Tripathi, D., Yadav S., Kumar-Chauhan, D., and Živčák, M., Ghorbanpour, M., El-Sheery, N.I., y Brestic, M. 2019. Application of silicon nanoparticles in agriculture, *Biotechnology, 3*, 9-90. DOI: 10.1007/s13205-019-1626-7.

Reyes-Pérez, J.J., Llerena-Ramos, L.T., Torres-Rodriguez, J.A., Hernández-Montiel, L.G., Macías-Pettao, R.K., Aragón-Sánchez, E., y Palacios-Espinosa, A. 2024. Silicio como bioestimulante en el cultivo del pepino (*Cucumis sativus* L.). *Tropical and Subtropical Agroecosystems, 27*, art. 123. https://doi.org/10.56369/tsaes.5359.

Rivera-Fernández, R.D, Pinos, H., Saltos, M., Bósquez, A., Camposano, C., y Verdezoto, C. 2021. Efecto del riego deficitario aplicado en etapa inicial del cultivo de pepino (*Cucumis sativus* L.) en un suelo franco. *Revista Ciencia y Tecnología, 14*(1), 55-60. DOI:https://doi.org/10.18779/cyt.v14i1.459.

Rivera-Guetierrez RG, Preciado-Rangel P, Fortiz-Hernández M, Betancourt-Galindo R, Yescas-Coronado P, Orozco-Vidal JA (2021) Nanopartículas de óxido de zinc y su efecto en el rendimiento y calidad de melón. *Revista Mexicana de Ciencias Agrícolas 12*: 791-803. https://doi.org/10.29312/remexca.v12i5.2987.

Saberi, R., Vatankhah, M., Hassanisaadi, M., and Varma, R.S. 2024. A review of chitosan nanoparticles: Nature's gift for transforming agriculture through smart and effective delivery mechanisms. I*nternational Journal of Biological Macromolecules, 60*(2):129522. https://doi.org/10.1016/j.ijbiomac.2024.129522.

Sangwan, S., P. Sharma, L. Wati and S. Mehta. 2023. Effect of chitosan nanoparticles on growth and physiology of crop plants. Engineered nanomaterials for sustainable agricultural production, soil improvement and stress management Chapter 4, 99-123. Eds: Azamal Husen. Wolaita Sodo University, Wolaita, Ethiopia. https://doi.org/10.1016/C2021-0-00054-7

Singleton, V.L., Orthofer, R., and Lamuela, R.M. 1999. Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. *Methods Enzymol. 299*:152-178. https://doi.org/10.1016/S0076-6879(99)99017-1

Sun, W., Shahrajabian, M.H., Petropoulos,S.A., and Shahrajabian, N. 2023. Developing Sustainable agriculture systems in medicinal and aromatic plant production by using chitosan and chitin-based biostimulants. *Plants, 12*(13), 24-69. DOI: https://doi.org/10.3390/plants12132469

Tejeda-Villagómez, E.A., Hernández-Adame, L., Nieto-Navarro, F., and Anzaldo-Montoya, M. 2023. Nanopartículas de silicio como vehículos de transporte para moléculas de interés agrícola. *Mundo Nano, 16*(30), 1e-20e. https://doi.org/10.22201/ceiich.24485691e.2023.30.69732.

Tymoszuk A, Wojnarowicz J (2020) Zinc oxide and zinc oxide nanoparticles impact on In vitro germination and seedling growth in Allium Cepa L. *Materials 13*: 2784. https://doi.org/10.3390/ma13122784.

Ucan-Tucuch, O., Betancourt-Galindo, R., Juárez-Maldonado, A., Sánchez-Vega, M., Sandoval-Rangel, A., y Méndez-López, A. 2023. Efecto de maltodextrinay nanoparticulas de óxido de zinc sobre biomasa y rendimiento en pepino. *Ecosistemas y Recursos Agropecuarios, 3*, e3699. DOI:10.19136/era.a10nIII.3699.

Velásquez, L., Pirela, L., Chirinos, A., y Avelizapa, I. 2019. Nuevos retos en agricultura para los biopolímeros de quitina y quitosano. Parte 1: efectos beneficiosos para los cultivos. *Revista Iberoamericana de Polímeros, 20*(3), 118-136. eviberpol.org/2019/05/01/nuevos-retos-en-agricultura-para-los-biopolimeros-de-quitina-y-quitosano-1-efectos-beneficiosos-para-los-cultivos/

Yan, G., Huang, Q., Zhao, S., Xu, Y., He, Y., Nikolic, M., Nikolic, N., Liang, Y., and Zhu, Z. 2024. Silicon nanoparticles in sustainable agriculture: synthesis, absorption, and plant stress alleviation. Front. *Plant Sci. 15*:1393458. DOI: 10.3389/fpls.2024.139345.

Zhishen, J., Mengcheng, T., and Jianming, W. 1999. The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food chemistry 64*(4):555-559. https://doi.org/10.1016/S0308-8146(98)00102-2