

Dose-response evaluation of chitosan, nanostructured silicon and micronutrient microcapsules on the yield of *Cucumis sativus* L. under greenhouse conditions

Evaluación dosis-respuesta de microencapsulados de quitosano, silicio nanoestructurado y micronutrientes sobre el rendimiento de *Cucumis sativus* L. bajo invernadero

Avaliação dose-resposta de microencapsulados de quitosana, silício nanoestruturado e micronutrientes sobre o rendimento de *Cucumis sativus* L. em casa de vegetação

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Abstract

The low efficiency of conventional fertilization limits nutrient use in intensive horticultural crops; therefore, microencapsulated bioinputs represent an alternative to improve cucumber productivity under greenhouse conditions. This study aimed to evaluate the dose-dependent response of growth, productive components and yield of *Cucumis sativus* L. to foliar application of chitosan and micronutrient microcapsules with SiO₂ nanoparticles. The experiment was carried out under greenhouse conditions at the Technical State University of Quevedo, Ecuador, with a mean internal temperature of 27.9 °C. A completely randomized design was used with four treatments and four replications: T1, control with basal fertilization and no foliar spraying; T2, 1,000 mg.L⁻¹; T3, 1,500 mg.L⁻¹; and T4, 2,000 mg.L⁻¹, sprayed at 12, 25 and 35 days after sowing with 100 mL.plant⁻¹ per application. Plant height, stem diameter, days to flowering, number of fruits per plant, fruit length, fruit diameter, fruit weight and yield per plot were assessed. The 2,000 mg.L⁻¹ dose showed the most consistent response, with 456.25 cm plant height at 60 days, 8.00 mm stem diameter, 3.00 fruits per plant, 30.28 cm fruit length, 5.67 cm fruit diameter and 6.72 kg per plot, equivalent to a projected 42.0 t.ha⁻¹ against 24.8 t.ha⁻¹ in the control. The 2,000 mg.L⁻¹ dose showed the best agronomic performance under the evaluated conditions, although validation in additional cycles is required.

Resumen

La baja eficiencia de la fertilización convencional limita el aprovechamiento de nutrientes en cultivos hortícolas intensivos, por lo que los bioinsumos microencapsulados representan una alternativa para mejorar el desempeño productivo del pepino bajo invernadero. El objetivo de la presente investigación fue evaluar la respuesta dosis-dependiente del crecimiento, los componentes productivos y el rendimiento de *Cucumis sativus* L. a la aplicación foliar de microencapsulados de quitosano y micronutrientes con nanopartículas de SiO₂. El estudio se realizó bajo invernadero en Quevedo, Ecuador, con temperatura interna promedio de 27,9 °C. Se empleó un diseño completamente al azar con cuatro tratamientos y cuatro repeticiones: T1, control con fertilización basal sin aspersión foliar; T2, 1.000 mg.L⁻¹; T3, 1.500 mg.L⁻¹; y T4, 2.000 mg.L⁻¹, aspersados a los 12, 25 y 35 días después de la siembra con 100 mL.planta⁻¹ por aplicación. Se evaluaron altura de planta, diámetro de tallo, días a floración, número y dimensiones del fruto y rendimiento por parcela. La dosis de 2.000 mg.L⁻¹ presentó la respuesta más consistente, con 456,25 cm de altura a los 60 días, 8,00 mm de diámetro de tallo, 3,00 frutos por planta, 30,28 cm de longitud y 5,67 cm de diámetro de fruto, y 6,72 kg por parcela, equivalentes a 42,0 t.ha⁻¹ proyectadas frente a 24,8 t.ha⁻¹ del control. La dosis de 2.000 mg.L⁻¹ presentó el mejor desempeño agronómico bajo las condiciones evaluadas, aunque requiere validación en ciclos adicionales.

Palabras clave: bioestimulación, eficiencia nutricional, fertilización foliar, nanotecnología agrícola.

Resumo

A baixa eficiência da fertilização convencional limita o aproveitamento de nutrientes em cultivos hortícolas intensivos; por isso, os bioinsumos microencapsulados representam uma alternativa para melhorar o desempenho produtivo do pepino em casa de vegetação. O objetivo desta pesquisa foi avaliar a resposta dose-dependente do crescimento, dos componentes produtivos e do rendimento de *Cucumis sativus* L. à aplicação foliar de microencapsulados de quitosana e micronutrientes com nanopartículas de SiO₂. O estudo foi realizado em casa de vegetação em Quevedo, Equador, com temperatura interna média de 27,9 °C. Utilizou-se delineamento inteiramente casualizado, com quatro tratamentos e quatro repetições: T1, controle com fertilização basal sem pulverização foliar; T2, 1.000 mg.L⁻¹; T3, 1.500 mg.L⁻¹; e T4, 2.000 mg.L⁻¹, pulverizados aos 12, 25 e 35 dias após a semeadura, com 100 mL.planta⁻¹ por aplicação. Foram avaliados altura de planta, diâmetro do caule, dias até a floração, número e dimensões do fruto e rendimento por parcela. A dose de 2.000 mg.L⁻¹ apresentou a resposta mais consistente, com 456,25 cm de altura aos 60 dias, 8,00 mm de diâmetro do caule, 3,00 frutos por planta, 30,28 cm de comprimento e 5,67 cm de diâmetro do fruto, e 6,72 kg por parcela, equivalentes a 42,0 t.ha⁻¹ projetadas frente a 24,8 t.ha⁻¹ do controle. A dose de 2.000 mg.L⁻¹ apresentou o melhor desempenho agronômico nas condições avaliadas, embora exija validação em ciclos adicionais.

Palavras-chave: bioestimulação, eficiência nutricional, fertilização foliar, nanotecnologia agrícola.

Introduction

The cucumber (*Cucumis sativus* L.) is a short-cycle vegetable in high commercial demand, widely used in protected cultivation due to its response to intensive agronomic management (Mahdy *et al.*, 2024; El-Mogy *et al.*, 2025). It is an annual, climbing cucurbit, grown in greenhouses using vertical trellising, whose staggered harvest sustains a continuous nutritional demand during fruit set (Sallam *et al.*, 2021). Its yield depends on the genetic potential of the cultivar and the sustained availability of water and nutrients during vegetative growth, flowering and fruit filling (Hu *et al.*, 2022; Shalaby *et al.*, 2021), which highlights the importance of designing more efficient nutritional strategies (Beig *et al.*, 2022; Haydar *et al.*, 2024).

One of the limitations of conventional fertilisation is that some of the applied nutrients are not available at the time of peak demand, due to leaching, immobilisation, volatilisation or low uptake efficiency (Beig *et al.*, 2022; Nongbet *et al.*, 2022), a critical limitation in intensive vegetable production, where demand shifts rapidly between vegetative growth and reproductive development (Feil *et al.*, 2021; Hu *et al.*, 2022). In response to this, controlled-release fertilisers and nanostructured systems have attracted attention for their ability to deliver nutrients gradually and reduce losses (Haydar *et al.*, 2024; Nongbet *et al.*, 2022).

Nanostructured silicon is of interest due to its role in tissue strengthening, physiological stability and stress tolerance, with effects that depend on the species, dose, particle size and route of application (Yan *et al.*, 2024; AlSaeedi, 2022). In cucumber, favourable responses to nanostructured silicon compounds have been reported in terms of growth, yield and fruit attributes under protected or stress conditions (Mahdy *et al.*, 2024; El-Mogy *et al.*, 2025; Shalaby *et al.*, 2021).

Chitosan, stands out as an agricultural biopolymer due to its biodegradability, low toxicity and biostimulant function in vegetables (Shahrajabian *et al.*, 2021; Stasińska-Jakubas and Hawrylak-Nowak, 2022), and acts as a matrix for the gradual release of nutrients and a platform for agronomaterials capable of encapsulating active compounds (Rojas-Pirela *et al.*, 2024; Ingle *et al.*, 2022; Chouhan and Mandal, 2021).

Micronutrients, in turn, play essential roles in enzymatic activity, photosynthesis, chlorophyll synthesis and metabolic regulation; their availability therefore influences growth and fruit set (Feil *et al.*, 2021; Nongbet *et al.*, 2022). In nanostructured or microencapsulated formulations, they can be incorporated into more controlled-release systems (Beig *et al.*, 2022; Haydar *et al.*, 2024); however, their efficacy cannot be generalised, as the plant response varies with dose, species, environment and agronomic management (Balusamy *et al.*, 2022).

The evidence on nutritional management in greenhouse cucumbers supports the evaluation of multi-component products rather than isolated nutrients. Sallam *et al.* (2021) reported that combining an organic source with an N:P:K ratio of 15:15:15 increased yield by up to 74.6 % and that multivariate analysis grouped the integrated treatments together as opposed to the control, indicating that the effect arises from the combination as a whole. Similarly, Hassan *et al.* (2021) observed improvements in yield and fruit composition when mineral fertilisation was partially replaced by a biostimulant. Chitosan microencapsulation has also been proposed as a platform for delivering nutrients with gradual release (García-Carrasco *et al.*, 2023).

Despite advances in nano-fertilisers, biostimulants and nanostructured sources of silicon, there is limited evidence regarding the agronomic response of cucumbers to integrated formulations combining chitosan, micronutrients and SiO₂ nanoparticles within a single microencapsulated system, as most studies evaluate isolated components or specific stress conditions. This gap is significant for growing regions that require alternatives capable of improving yield without replacing base fertilisation.

In light of this issue, the aim of this study was to evaluate the dose-dependent response of cucumber growth, productive components and yield to the foliar application of microencapsulated chitosan and micronutrients with SiO₂ nanoparticles under greenhouse conditions. The experiment assessed the response to the complete formulation and was not designed to separate the individual effects of chitosan, SiO₂, micronutrients, N:P:K fertiliser or the microencapsulation process.

Materials and methods

Experimental location

The research was carried out under greenhouse conditions at the Facultad de Ciencias Agrarias y Forestales, Universidad Técnica Estatal de Quevedo, 'La María' Experimental Campus, km 7.5 on the Quevedo–El Empalme road, Los Ríos, Ecuador, at 01°04'48.6" south latitude and 79°30'04.2" west longitude, at an elevation of 66.1 m above sea level. The area has a humid tropical climate, with an average annual temperature of 24.9 °C, an average relative humidity of 84 % and average annual rainfall of 2,295.1 mm. During the trial, an average temperature of 27.9 °C was recorded inside the greenhouse.

Plant material and crop establishment

The 'Rocco' cultivar of cucumber (*C. sativus*) was used. Pre-sowing was carried out in seed trays using a light substrate based on worm castings, selected for its aeration and drainage properties during emergence, with two seeds placed per cell. Between 4 and 6 days after emergence, the seedlings were transplanted into the greenhouse into 10 × 12-inch perforated polyethylene bags, filled with 10 kg of substrate carefully compacted to avoid air pockets. The transplanting substrate consisted of sieved black soil and compost in a 3:1 (v/v) ratio, which was common to all experimental units.

Growing medium and basal fertilisation

Prior to transplanting, a uniform basal fertiliser application equivalent to 1.20 g of N, 1.20 g of P₂O₅ and 1.20 g of K₂O per plant was incorporated into the growing medium in the pots. The fertilisers were distributed evenly throughout the growing medium before the seedlings were established. This fertilisation constituted the conventional nutritional basis of the trial and was common to all four treatments; consequently, treatment T1 corresponds to conventional fertilisation practice without foliar spraying and serves as the reference control against the increasing doses of the microencapsulated formulation.

Treatments evaluated

The factor under investigation was the dose of chitosan microencapsulates and micronutrients with SiO₂ nanoparticles. Four treatments were evaluated: T1, control without foliar spraying; T2, 1,000 mg.L⁻¹; T3, 1,500 mg.L⁻¹; and T4, 2,000 mg.L⁻¹. The formulation consisted of silicon dioxide nanoparticles doped 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, coated in a chitosan matrix with 15:15:15 N:P:K fertiliser. The formulation was produced in the Chemistry Laboratory at the Universidad Técnica

Estatal de Quevedo, and is not a commercial product. The synthesis and physicochemical characterisation were not part of this study, the aim of which was to investigate the agronomic response of the crop. The application was carried out by foliar spraying using a hand-held sprayer, ensuring uniform coverage, at 12, 25 and 35 days after sowing, at a rate of 100 mL.plant⁻¹; the cumulative dose corresponded to 300, 450 and 600 mg.plant⁻¹ in T2, T3 and T4, respectively. The control plot was managed in the same way, without application of the formulation.

Experimental design

A completely randomised design was used, given the relative homogeneity of the growing conditions within the greenhouse, with four treatments and four replicates, making a total of 16 experimental units. Each unit consisted of four plants arranged in two rows with two plants per row, with 1.0 m between rows, 0.40 m between plants and 0.80 m between replicates, making a total of 64 plants. The treatments were assigned at random and, for the analysis, the plot of four plants was considered the experimental unit, with the records per plant averaged prior to the analysis of variance.

Agronomic management

Irrigation was carried out manually using watering cans, with water sourced from a deep well at the 'La María' Experimental Campus. During the early stages of growth, approximately 2 L.plant⁻¹ was applied per irrigation event, three times a week. As vegetative growth and water demand increased, the volume was progressively raised to 4 L.plant⁻¹ per irrigation, and the frequency was adjusted to two waterings per week. The same irrigation regime was applied uniformly across all treatments. Pruning was carried out weekly, removing broken, diseased or senescent leaves and unwanted shoots. Staking began at 15 days, when the main shoots appeared, using twine to guide vertical growth and reduce contact with the ground. Plant protection management and other cultural practices were standard across all experimental units, so that the dose of the microencapsulated formulation was the sole source of variation. Harvesting took place when the fruits reached commercial maturity, between 75 and 90 days after transplanting.

Morphometric variables

Plant height was assessed at 45 and 60 days after sowing, measured from the base of the stem to the apex of the youngest leaf; the values were expressed in centimetres. Stem diameter was recorded at the same time points, 5 cm above the base, using a digital vernier caliper; values were expressed in millimetres. Both variables were recorded at two specific time points during the cycle and do not derive from a growth analysis in the strict sense; they are therefore interpreted as morphometric descriptors of vegetative development.

Yield variables

Days to flowering were recorded as the number of days from sowing until 50 per cent of the plants in the experimental plot had at least one fully open flower. The number of fruits per plant was determined by direct counting. Fruit length was measured from the base to the apex using a tape measure, and the diameter at the equatorial region was measured using a digital vernier caliper, both expressed in centimetres. Fruit weight was recorded using an Ohaus digital balance and expressed in grams. Yield per plot was calculated from the cumulative weight of the fruits harvested within the usable area of each experimental unit and expressed in kilograms.

Estimation of projected yield

Based on the planting pattern used, with 1.0 m between rows and 0.40 m between plants, each plant occupied 0.40 m², which equates

to a theoretical density of 25,000 plants.ha⁻¹. The projected yield per hectare was estimated by multiplying the average yield per plant for each treatment by this density. This estimate is an arithmetic extrapolation for comparative purposes and does not replace validation on commercial plots.

Statistical analysis

The data were subjected to the Shapiro-Wilk test to verify the normality of the residuals, and to Levene’s test to check for homogeneity of variances; both assumptions were met for all variables, except for marginal heterogeneity in fruit diameter (Levene, $p = 0.035$), the significance of which was confirmed using robust tests. Subsequently, an analysis of variance was carried out in accordance with a completely randomised design and, where significant differences were detected, the means were compared using Tukey’s test at a 5 % significance level. As the dose was a quantitative factor, linear and quadratic regression models were additionally fitted for each variable as a function of concentrations of 0; 1,000; 1,500 and 2,000 mg.L⁻¹, using the 16 experimental units, and the significance of the linear and quadratic terms was assessed at $\alpha = 0.05$. All analyses were performed using the InfoStat software, version 2020.

Results and discussion

Analysis of variance showed that foliar application of the microencapsulated formulation significantly altered most of the variables assessed (Table 1): plant height and stem diameter at 45 and 60 days, number of fruits per plant, fruit length and diameter, and yield per plot. By contrast, individual fruit weight did not show any significant differences and, although the number of days to flowering proved significant in the overall analysis, Tukey’s test did not distinguish between the treatments.

Table 1. Summary of the analysis of variance for morphometric variables, flowering, fruit components and cucumber yield following the application of microencapsulated chitosan, micronutrients and SiO₂ nanoparticles.

Variable	R ²	Adjusted R ²	CV (%)	p-value
Plant height at 45 days	0.66	0.57	4.06	0.0039
Plant height at 60 days	0.65	0.56	3.58	0.0045
Stem diameter at 45 days	0.50	0.37	6.71	0.0348
Stem diameter at 60 days	0.68	0.60	4.23	0.0026
Days to flowering	0.47	0.34	2.03	0.0488
Number of fruits per plant	0.55	0.44	11.98	0.0184
Fruit length	0.49	0.37	5.23	0.0369
Fruit diameter	0.66	0.57	3.24	0.0038
Fruit weight	0.43	0.29	10.89	0.0699
Yield per plot	0.93	0.91	6.00	<0.0001

CV: coefficient of variation. Differences were considered significant when $p < 0.05$. The adjusted R² corrects the coefficient of determination for the number of model parameters and the sample size; its calculation did not involve the removal of any variables.

Vegetative growth responded positively to the increase in dose (Figure 1). At 45 days, T4 reached the greatest height at 181.62 cm, followed by T3 and T2 at 180.31 and 175.75 cm, compared with 160.19 cm for the control; at 60 days, T4 maintained the greatest response at 456.25 cm compared with 405.69 cm. Stem diameter showed a similar pattern: T4 reached 6.62 mm at 45 days and 8.00 mm at 60 days, compared with 5.69 and 6.88 mm for the control. The

greater height and stem diameter observed are consistent with a more vigorous vegetative response; however, the study did not directly assess hydraulic conduction or the transport of photoassimilates to the reproductive organs.

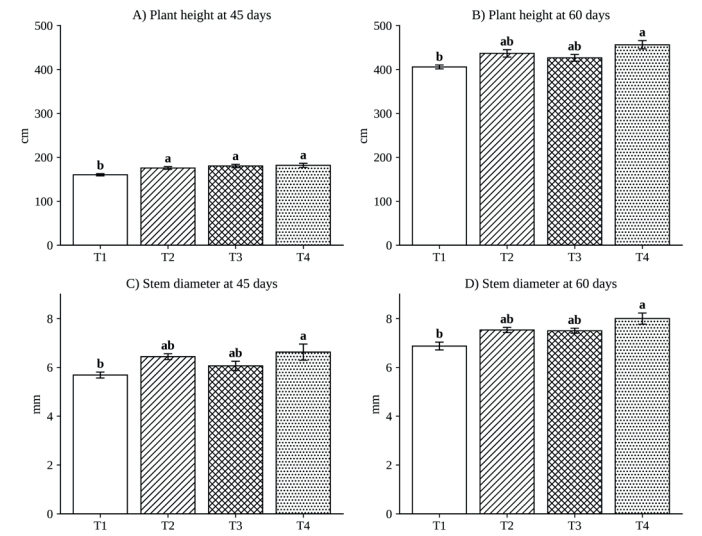


Figure 1. Morphometric response of the ‘Rocco’ cucumber cultivar to increasing doses of microencapsulated chitosan, micronutrients and SiO₂ nanoparticles. Panels for the same variable share the same scale. Means ± standard error (n = 4); different letters indicate significant differences according to Tukey’s test ($p \leq 0.05$).

The vegetative behaviour is consistent with the biostimulant role attributed to chitosan in horticultural crops, which is described as a biodegradable material with low toxicity and the ability to induce growth, defence and tolerance responses (Shahrajabian *et al.*, 2021; Rojas-Pirela *et al.*, 2024). This interpretation should be treated as an explanatory hypothesis, as the study did not include measurements of photosynthesis, enzymatic activity, mineral uptake or internal nutrient concentrations.

From a functional perspective, the elements in the formulation can be grouped according to the stage at which their metabolic role is most significant, although this does not imply that individual effects are attributed to them in this study. Zinc is involved in the synthesis of tryptophan and, via this route, in the biosynthesis of auxins; manganese is involved in the oxygen-evolving complex of photosystem II; iron is involved in chlorophyll formation and in redox reactions; and copper is associated with lignification and pollen formation (Hänsch and Mendel, 2009). This set of elements corresponds to the morphometric variables that responded to the dose. For its part, B plays a decisive role in cell wall synthesis, pollen tube growth, fruit set and final fruit size (Álvarez-Herrera *et al.*, 2025), whilst Ca stabilises cell walls and membranes and Mo acts as a cofactor for nitrate reductase (Hänsch and Mendel, 2009), a grouping consistent with the increase in fruit number and size. This is, however, a functional interpretation supported by the literature rather than an experimental demonstration, given that the design did not include isolated components or measurements of internal nutrient concentrations.

The days to flowering proved significant in the analysis of variance ($p = 0.049$); however, Tukey’s test did not detect any paired differences between treatments. The values ranged from

45.25 days in T3 to 47.00 days in T2, with 45.50 days in T4 and 46.75 days in the control, meaning that the magnitude of the differences is of no agronomic significance. The result also suggests a further interpretation: the greater vegetative growth in T4 was not accompanied by a delay in flowering, meaning that the stimulation of growth did not compromise the transition to the reproductive phase, an aspect of interest in a short-cycle vegetable.

The number of fruits per plant increased significantly with the dose (Figure 2): the control recorded 2.19 fruits and T4 reached 3.00, a difference supported by Tukey's test (T1 = b; T4 = a; T2 and T3 in an intermediate position). Fruit dimensions also responded: length increased from 26.77 cm in the control to 30.28 cm in T4, and diameter increased from 5.11 to 5.67 cm, with significant differences compared with the control. In contrast, individual fruit weight, which ranged from 454.49 g in the control to 573.21 g in T4, showed no statistically significant differences ($p = 0.070$); thus, the effect on physical quality was reflected in the fruit's dimensions rather than its weight.

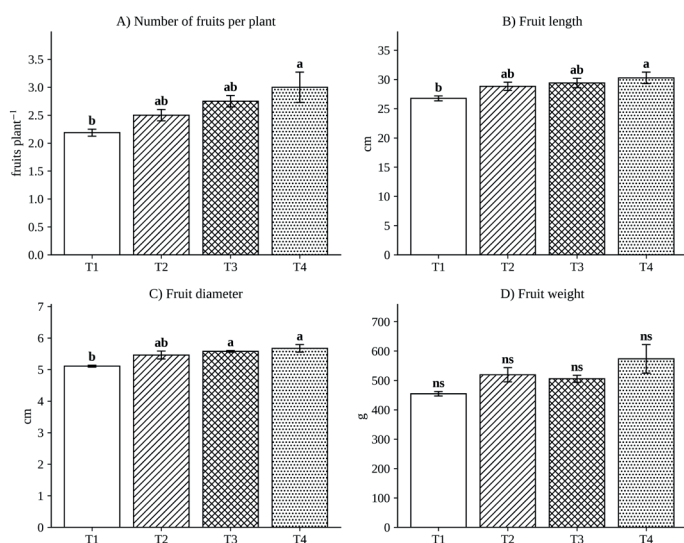


Figure 2. Productive components of the fruit of the 'Rocco' cucumber cultivar under increasing doses of microencapsulated chitosan, micronutrients and SiO_2 nanoparticles. Means $\pm$ standard error ($n = 4$); different letters indicate significant differences according to Tukey's test ($p \leq 0.05$). ns: not significant (fruit weight, $p = 0.070$).

It should be noted that the numerical order observed between T2 (519.18 g) and T3 (505.48 g) in terms of individual fruit weight does not constitute a reversal of the dose-response trend: as there were no significant differences ($p = 0.070$) and this variable exhibited one of the highest coefficients of variation in the trial (10.89 %), the difference of 13.70 g between the two doses falls within the experimental error (± 24.22 and ± 11.73 g, respectively) and should not be attributed to the treatments or to agronomic management, which was uniform.

Nanostructured silicon is key to interpreting this response, as its nanoparticles are involved in absorption, translocation and stress mitigation, with effects that depend on dose, species and environment (Yan *et al.*, 2024). In cucumber, trials with nano-calcium and nano-silicon under protected conditions reported improvements in growth, fruit weight and yield (Mahdy *et al.*, 2024), and the foliar application of Ca, K and Si nanoparticles, as well as nano-selenium and silicon under salinity and heat, enhanced productivity (El-Mogy *et al.*, 2025;

Shalaby *et al.*, 2021). This convergence does not imply equivalence between formulations, but places the results within a broader experimental trend.

Yield per plot incorporated the agronomic response of the crop and was the most robust effect in the trial ($p < 0.0001$; Figure 3). The control yielded 3.97 kg; T2 and T3 yielded 5.18 and 5.55 kg respectively, whilst T4 recorded the highest value at 6.72 kg. The Tukey test distinguished three levels (T1 = c; T2 and T3 = b; T4 = a), confirming that the dose of $2,000 \text{ mg.L}^{-1}$ was the most efficient within the range evaluated. Based on the theoretical density of $25,000 \text{ plants.ha}^{-1}$ derived from the planting pattern, these values correspond to projected yields of 24.8; 32.4; 34.7 and 42.0 t.ha^{-1} for T1, T2, T3 and T4, respectively, that is, a 69.3 % increase for T4 compared with the control using conventional basal fertilisation.

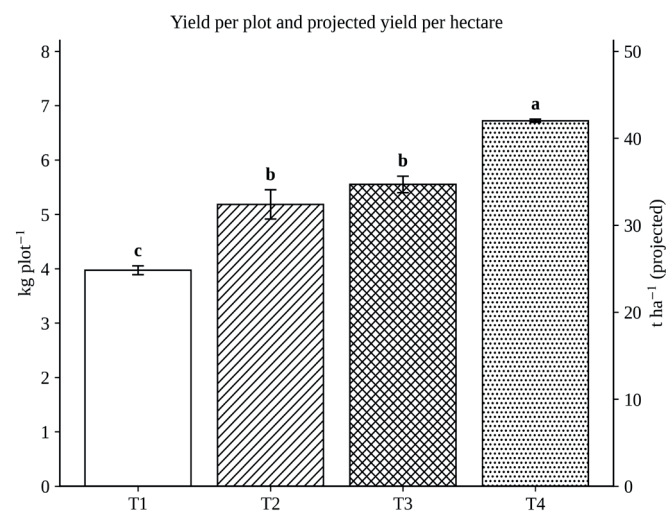


Figure 3. Yield per plot of 'Rocco' cucumber under increasing doses of microencapsulated chitosan, micronutrients and SiO_2 nanoparticles. The secondary axis shows the projection at $25,000 \text{ plants.ha}^{-1}$. Means $\pm$ standard error ($n = 4$); different letters indicate significant differences according to Tukey's test ($p \leq 0.05$).

The improvement in yield is consistent with the hypothesis of more sustained nutrient availability. Reviews on slow- and controlled-release nanofertilisers indicate that these systems regulate nutrient delivery, reduce losses and improve nutrient use efficiency (Haydar *et al.*, 2024; Nongbet *et al.*, 2022), and in *Cucumis sativus*, functionalised nanoparticles modify the plant's nutritional dynamics (Feil *et al.*, 2021). However, the release kinetics and mineral uptake were not directly assessed in this trial; therefore, this mechanism requires further verification.

It is worth comparing this magnitude with that reported for conventional fertilisation in the same crop. Sallam *et al.* (2021), in greenhouse-grown cucumber fertilised with N:P:K 15:15:15 combined with an organic source, recorded increases of up to 74.6 % compared with the control, a figure of the same order as the 69.3 % obtained here with $2,000 \text{ mg.L}^{-1}$ on a conventional fertilisation basis. Similarly, Hassan *et al.* (2021) achieved improvements in yield and fruit chemical composition by partially replacing mineral fertilisation with a biostimulant. The formulation evaluated therefore falls within the expected range for integrated nutrient management in cucumber, with the particular feature of acting as a foliar supplement to basal fertilisation rather than as a substitute for it.

The main limitation of the design is the absence of controls using N:P:K alone, a formulation without N:P:K, and treatments with individual components; consequently, the observed effect cannot be attributed to a specific ingredient nor does it demonstrate synergy, but rather corresponds to the complete formulation applied on top of a conventional fertilisation regime. Furthermore, the harvest period was recorded in aggregate (75 to 90 days after transplanting), without a breakdown by treatment; consequently, it is not possible to assess effects on the earliness or extension of the productive window, a variable recommended for subsequent validation cycles.

Dose-response relationships

As dose was a quantitative factor, regression models were fitted for each variable against the concentration applied. Yield per plot showed the strongest and most linear relationship ($R^2 = 0.89$; $p < 0.001$), with the quadratic term not being significant ($p = 0.152$); similar linear patterns were observed for fruit diameter ($R^2 = 0.65$), the number of fruits per plant ($R^2 = 0.54$) and fruit length ($R^2 = 0.49$). The absence of a quadratic component merely indicates that no plateau was observed within the range evaluated; therefore, the results should not be extrapolated beyond 2,000 mg.L⁻¹.

Conclusions

Foliar application of the microencapsulated formulation evaluated improved the vegetative growth and yield performance of cucumber under greenhouse conditions. The dose of 2,000 mg.L⁻¹ produced the most consistent agronomic response, recording the highest values for plant height, stem diameter, number of fruits per plant, fruit length and diameter, and yield per plot, at 6.72 kg per plot, equivalent to a projected yield of 42.0 t.ha⁻¹ compared with 24.8 t.ha⁻¹ for the control treated with conventional basal fertilisation.

The increase in yield is associated with a higher number of fruits per plant and with larger fruits, rather than with individual fruit weight, which does not differ significantly between treatments. The dose of 2,000 mg.L⁻¹ combines these components, which explains its superiority over the control and the lower doses. These results relate to the complete formulation applied as a foliar supplement to the basal fertilisation and do not allow the effect to be attributed to any one of its components in isolation.

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