

## Effect of Protein Hydrolysates and Diatomaceous Soil as Biostimulants on Hydroponic Grape Tomato Efecto de Hidrolizados Proteicos y Diatomeas como Bioestimulantes en el Cultivo Hidropónico de Tomate Uva

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### SUMMARY

The search for non-microbial biostimulants to optimize sustainable hydroponic production is a rapidly expanding research area; however, the synergistic effect between protein hydrolysates and silicon (Si) in horticultural crops has not yet been fully elucidated. This study evaluated the biostimulant effect of the combined application of three protein hydrolysates (animal, plant, and mixed-origin) and three Si concentrations (10, 15, and 20 mg L<sup>-1</sup>) on growth, yield, and net CO<sub>2</sub> assimilation rate of grape tomato plants (*Solanum lycopersicum* L.) grown in a hydroponic system, as well as on the chemical characteristics of the substrate and leachate. A randomized complete block design with a 3 × 3 factorial arrangement was used, with four replications. Results showed that the plant-derived hydrolysate exhibited the greatest biostimulant potential by increasing biomass production, fruit size, weight, yield, and net photosynthetic rate, while reducing total soluble solids. Si increased net CO<sub>2</sub> assimilation at 20 mg L<sup>-1</sup> without affecting fruit size or yield. In the substrate, the plant-derived hydrolysate raised pH and decreased electrical conductivity and nitrate levels, suggesting greater nitrogen use efficiency. Potassium was not influenced by the hydrolysate but was affected by Si doses, particularly at 10 and 20 mg L<sup>-1</sup>. No significant interactions between the two factors were detected for most evaluated variables. The application of plant-derived protein hydrolysate enhances grape tomato growth and yield, promoting a more stable root-zone environment and greater efficiency in nitrate assimilation.

**Index words:** *biostimulation, silicon, soilless cultivation, Solanum lycopersicum.*

### RESUMEN

La búsqueda de bioestimulantes no microbianos para optimizar la producción hidropónica sustentable es un área de investigación en constante expansión; sin embargo, el efecto sinérgico entre los hidrolizados proteicos y el silicio (Si) en cultivos hortícolas aún no ha sido completamente dilucidado. El presente estudio evaluó el efecto bioestimulante de la aplicación conjunta de tres hidrolizados proteicos (de origen animal, vegetal y mixto) y tres concentraciones de Si (10, 15 y 20 mg L<sup>-1</sup>) sobre el crecimiento, el rendimiento y la tasa de asimilación neta de CO<sub>2</sub> de las plantas de tomate uva (*Solanum lycopersicum* L.) cultivadas en sistema hidropónico, así como sobre las características químicas del sustrato y del lixiviado. Se utilizó un diseño de bloques completos al azar con arreglo factorial 3 × 3, con cuatro réplicas.



#### Recommended citation:

Lozano-Cavazos, C. J., García-Santiago, J. C., Zermeño-González, A., Rivas-García, T., Zúñiga-Gracia, D. A., & Preciado-Rangel, P. (2026). Effect of Protein Hydrolysates and Diatomaceous Soil as Biostimulants on Hydroponic Grape Tomato. *Terra Latinoamericana*, 44, 1-11. e2502. <https://doi.org/10.28940/terralatinoamericana.v44i.2502>

Received: December 18, 2025.

Accepted: February 04, 2026.

Article, Volume 44.

May 2026.

Section Editor:

Dr. Fidel Núñez-Ramírez

Technical Editor:

M.C. Ayenía Carolina Rosales Nieblas



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Los resultados mostraron que el hidrolizado de origen vegetal mostró mayor potencial bioestimulante al incrementar la producción de biomasa, tamaño, peso, rendimiento de frutos, así como la tasa fotosintética neta, pero una reducción de los sólidos solubles totales. El Si elevó la asimilación neta de CO<sub>2</sub> a 20 mg L<sup>-1</sup> sin afectar el tamaño ni rendimiento. En el sustrato, el hidrolizado vegetal aumentó el pH del sustrato y disminuyó la conductividad eléctrica y los nitratos, lo que sugiere mayor eficiencia en el uso del nitrógeno. El potasio no fue afectado por el hidrolizado, pero sí por las dosis de Si, especialmente con las dosis de 10 y 20 mg L<sup>-1</sup>. No se detectaron interacciones significativas entre ambos factores para la mayoría de las variables evaluadas. La aplicación de hidrolizado proteico de origen vegetal, mejora el crecimiento y el rendimiento del tomate uva y promueve un ambiente radicular más estable y una mayor eficiencia en la asimilación de nitratos.

**Palabras clave:** bioestimulación, silicio, cultivo sin suelo, *Solanum lycopersicum*.

## INTRODUCTION

In modern agriculture, the development of strategies that promote crop growth and productivity is essential for achieving more efficient and sustainable systems. In this context, protein hydrolysates have emerged as a promising tool in sustainable agriculture (Dhanasekaran *et al.*, 2025). These compounds consist of mixtures of polypeptides, oligopeptides, and free amino acids obtained through partial (chemical or enzymatic) hydrolysis of animal- or plant-based agro-industrial by-products (Chura and Montero, 2025). In particular, protein hydrolysates derived from agro-industrial byproducts are considered more environmentally friendly due to the valorization of waste materials and reduced environmental impact (Xu and Geelen, 2018). Their application in crops has been associated with increased nutrient uptake, growth, yield, fruit quality, and crop tolerance to abiotic stress (Sun, Shahrajabian, Kuang, and Wang, 2024; Pasković *et al.*, 2024).

The biostimulant effects of protein hydrolysates are attributed to the activation of enzymes involved in nitrogen assimilation, such as nitrate reductase and glutamine synthetase, which may enhance carbon assimilation and increase the activity of metabolic pathways related to plant growth (Ertani *et al.*, 2009; Casadesús, Pérez, Munné, and Polo, 2020); however, their chemical composition and antioxidant capacity depend on the source material and the hydrolysis method used for their production (Czelej, Garbacz, Czernecki, Wawrzykowski, and Waśko, 2022).

It has been demonstrated that animal-based protein hydrolysates can increase plant tolerance to abiotic stress (water stress, salinity stress, extreme temperatures, and phytotoxicity) and improve plant resource use efficiency (RUE) (Carrillo *et al.*, 2022). Plant-based protein hydrolysates can improve yield and quality, stimulate carbon and nitrogen metabolism, enhance tolerance to abiotic stresses, and improve RUE (Colla, Cardarelli, Bonini, and Roupael, 2017; Roupael *et al.*, 2017; Lucini *et al.*, 2018). In addition, they may contain bioactive peptides capable of inducing auxin- and gibberellin-like actions, thereby increasing the density, number, length, and surface area of lateral roots and, indirectly, enhancing nutrient use and uptake efficiency, plant growth, and yield (Pasković *et al.*, 2024).

Diatoms are unicellular algae (~1-500 µm in length) belonging to the class *Bacillariophyceae*, division *Bacillariophyta*, and are classified as either central or pennate orders due to their morphology or habitat. They absorb silicon from the environment and deposit it in their cell walls, forming frustules that are complex, homogeneous, and mesoporous siliceous nanostructures (Mishra, Arukha, Bashir, Yadav, and Prasad, 2017). The role of silicon (Si) is essential and multifaceted for the development and resilience of crops (Reyes-Pérez *et al.*, 2024), making it an important component for enhancing their productivity and sustainability (Hernández-Juárez, 2024). In horticultural crops, silicon (Si) is considered a non-essential element; however, in recent years, it has gained significant interest in soilless cultivation systems (Koukounaras, 2021).

Silicon (Si) is a beneficial nutrient that promotes plant growth and development (Zhu and Gong, 2014; Azad *et al.*, 2021), and has demonstrated its biostimulant potential for mitigating abiotic stress in plants (Costan *et al.*, 2020), due to its ability to modify plant architecture, promoting more erect leaves, increasing solar radiation interception, and photosynthetic efficiency (Mandlik *et al.*, 2020). Furthermore, it participates in strengthening cell walls, synthesizing defense metabolites, and regulating genes associated with stress tolerance (Lozano, Almeida, Molina, Reyes, and López, 2025).

Consequently, the objective of this study was to evaluate the effects of three protein hydrolysates, from different sources, and three Si concentrations on biomass production, yield, and net CO<sub>2</sub> assimilation in grape tomato plants cv. Luciplus, as well as their influence on the chemical properties of the substrate and leachate from the hydroponic system.

## MATERIALS AND METHODS

### Location and Experimental Conditions

The study was conducted in a greenhouse at the Universidad Autónoma Agraria Antonio Narro, in Saltillo, Coahuila, Mexico (25° 21' N, 101° 02' W; 1759 m of altitude). The average environmental conditions during the cycle were: daily temperature, 19.1 °C; relative humidity, 71%; and the incident photosynthetically active radiation (PAR) during the peak sunlight period was 568  $\mu\text{mol m}^{-2} \text{s}^{-1}$ .

### Plant Material and Crop Management

Grape tomato (*Solanum lycopersicum* L.) seedlings cv. Luciplus (Hazera Genetics Ltd., Brurim MP Shikmim, Israel) was used. These were transplanted into black polyethylene containers (10 L), which contained a mixture of sphagnum peat and perlite (80:20 v/v) as substrate. Each plant was managed with two stems.

### Treatments and Experimental Design

A complete block design in a 3 × 3 factorial arrangement was used, with four replications. Each experimental unit consisted of two containers, each with one plant. The factors studied were: three OMRI-listed protein hydrolysates (animal origin, plant origin, and mixed) as N, P, and K sources (Mar y Tierra® Organic Fertilizers), and three silicon concentrations (10, 15, and 20 mg L<sup>-1</sup>), applied as Diatomix® (92.8% SiO<sub>2</sub>). Silicon doses (10, 15, and 20 mg L<sup>-1</sup>) were established based on the Si content of SiO<sub>2</sub>. Considering that Si represents 46.7% of the molecular weight of SiO<sub>2</sub>, the desired concentrations were converted to their SiO<sub>2</sub> equivalents. The nutritional composition of the specific hydrolysates used is detailed in Table 1. All nutrient solutions were formulated to deliver identical target concentrations of essential nutrients (in mg L<sup>-1</sup>): 168 N, 31 P, 273 K, 180 Ca, 48 Mg, and 112 S.

The hydrolysates provided all nitrogen (N) and phosphorus (P), and part of the potassium (K). To reach the target levels of potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), commercial organic fertilizers were used as supplements: Allganic® potassium 0-0-52-18 (K, S; SQM), Fijaflor (8% Ca; APELSA Guadalajara, S. A. de C. V.), and Bioflora Mg (4% Mg; Global Organics®). The initial composition of the irrigation water was considered when preparing the solution. All nutrient sources used were of natural origin. The nutrient solution was applied starting three days after transplanting. Irrigation was performed manually, adding the necessary amount of nutrient solution to maintain a leaching fraction of 25%.

### Variables Measured

The experiment concluded after 110 days post-transplantation. In all harvested fruits, weight, transverse diameter, and longitudinal diameter were measured, with the latter two determined using a digital caliper (Mitutoyo®). Yield per plant was calculated by summing the weight of all fruits harvested per plant. Total soluble solids were measured in the juice of each harvested fruit using a digital refractometer (ATAGO®, PAL-1). Net CO<sub>2</sub> assimilation was measured using a LI-COR 6800 portable photosynthesis system (LI-COR 6800, Lincoln, Nebraska). Measurements were conducted under photosynthetically active radiation (PAR) of 800  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , with light quality set to 0.84 red, 0.70 green, and 0.87 blue. The chamber air temperature was maintained at 35 °C, and the average leaf temperature during measurements was 28 °C. The fresh weight of each organ and the total fresh weight per plant were recorded immediately after harvesting by separating each plant into stems, leaves, and roots, weighing each organ, and summing these to obtain the total. The organs were then dried in a forced-air oven at 70 °C until constant weight was reached (approximately 72 hours) to determine the dry matter weight of each organ and the total dry weight.

**Table 1. Commercial products are used as sources of protein hydrolysates.**

Hydrolysed Origin	Commercial Product (Mar y Tierra®)	Composition (N-P-K)
Animal	5-7-1	5-7-1
	4-1-1	4-1-1
Vegetal	3-2-2	3-2-2
Animal-Plant	5-3-2	5-3-2

At the end of the experiment, pH, electrical conductivity (EC), nitrate ( $\text{NO}_3^-$ ), and potassium (K) levels were measured in both the substrate and the collected leachate. To evaluate the substrate, a representative sample was taken from the middle portion of each container. The sample was mixed with distilled water in a 1:2 ratio (30 ml of substrate: 60 ml of distilled water), allowed to settle for 30 minutes, and then filtered. Substrate chemical properties were measured using portable ion meters (Horiba LAQUA Twin) by placing 0.5 ml of the filtered sample onto each meter. Prior to measurement, the ion meters were calibrated at two points using the corresponding standard solutions. Leachate was collected two hours after irrigation, starting three days after transplanting when irrigation with nutrient solution began, and measurements continued monthly until the end of the experiment. For chemical analysis of the leachate, 0.5 ml of the sample was placed on the ion meters.

### Statistical Analysis

The assumptions of normality and homoscedasticity were verified for each variable using the Kolmogorov-Smirnov and Levene tests, respectively. Data transformation was not required. The data obtained were subjected to a two-way analysis of variance (ANOVA). Differences between treatment means were compared using Tukey's test ( $p \leq 0.05$ ) with SAS software (Statistical Analysis Systems), version 9.1. (SAS, 2003)

## RESULTS AND DISCUSSION

### Fresh and Dry Biomass

Biomass variables (fresh and dry weight of leaves, roots, and total) showed significant differences based on the hydrolysate source (Table 2), while the application of silicon did not affect these variables. The plant-based hydrolysate promoted the highest accumulation of aerial and total biomass, at the expense of reduced root development. No significant interaction was detected between the type of hydrolysate and the silicon dose. This behavior aligns with the biostimulant role of protein hydrolysates in modulating molecular and physiological processes that promote plant growth (Yakhin, Lubyantsev, Yakhin, and Brown, 2017). Their effectiveness depends on the origin and production method (Consentino *et al.*, 2020).

In this study, the plant-based hydrolysate obtained by enzymatic hydrolysis showed higher biomass production. This finding is consistent with that reported by Cerdán, Sánchez, Oliver, Juárez, and Sánchez (2009), who observed greater vegetative growth with plant-based hydrolysates compared to animal-based ones. This response may be attributed to their lower free amino acid content and higher proportion of soluble peptides, carbohydrates, phenols, and phytohormones, which contribute to the biostimulant action (Rivas-García *et al.*, 2021; Sánchez, 2024). In contrast, animal-based and mixed-origin hydrolysates contain a greater quantity of free amino acids relative to peptides, especially when produced by chemical hydrolysis, which can lead to excessive amino acid uptake, intracellular imbalance, energy expenditure, and inhibition of nitrate absorption (Meléndez, Ramírez, Montejo, López, and Pérez, 2024; Ramos-Abad, Campos, Condor, Toribio, and Rueda, 2025); The reduced root development observed with the plant-based hydrolysate could be explained by a preferential redistribution of photoassimilates to the aerial parts under favorable nutritional conditions (Wang and Ruan, 2016; Qi, Wei, Chen, and Chen, 2019).

**Table 2. Effect of protein hydrolysate origin and Si concentration on leaf fresh weight, root fresh weight, stem fresh weight, total fresh weight, leaf dry weight, root dry weight, stem dry weight, and total dry weight of grape tomato plants cv. Luciflus.**

	Fresh Weight (g plant <sup>-1</sup> )				Dry weight (g plant <sup>-1</sup> )			
	Leaf	Root	Stem	Total	Leaf	Root	Stem	Total
Hydrolysate Origin								
Animal	521.4 ± 43.8 b	16.5 ± 9.0 a	232.8 ± 30.5a	770.7 ± 72.4b	78.1 ± 3.6 b	2.59 ± 0.5 a	49.9 ± 5.1 a	130.5 ± 7.8 b
Plant	622.1 ± 52.9 a	10.0 ± 3.2 b	228.6 ± 30.8a	860.7 ± 64.8a	81.4 ± 6.8 a	1.89 ± 0.6 b	48.5 ± 5.3 a	131.7 ± 10.6 a
Animal-Plant	506.6 ± 57.7 b	11.5 ± 3.1 ab	210.3 ± 32.7a	728.4 ± 81.2b	74.1 ± 6.8 b	2.02 ± 0.4 ab	46.5 ± 4.4 a	122.6 ± 9.9 b
Si (mg L <sup>-1</sup> )								
10	528.5 ± 44.1 a	13.2 ± 9.08 a	226.0 ± 25.9a	767.7 ± 56.3a	75.7 ± 5.8 a	2.3 ± 1.1 a	48.2 ± 4.3 a	126.1 ± 9.2 a
15	557.9 ± 75.0 a	13.0 ± 5.6 a	222.5 ± 38.9a	793.4 ± 106.3a	78.4 ± 6.5 a	2.2 ± 0.7 a	48.8 ± 5.5 a	129.3 ± 11.0 a
20	563.7 ± 91.2 a	11.8 ± 3.4 a	223.1 ± 32.5a	798.6 ± 104.5a	79.5 ± 7.1 a	2.0 ± 0.5 a	47.9 ± 5.5 a	129.4 ± 10.5 a
Interaction	NS	NS	NS	NS	NS	NS	NS	NS

Means within the same column followed by the same letter are not significantly different, according to Tukey's test ( $p \leq 0.05$ ).

Silicon represents an interesting practice in organic production aimed at improving the development of various crops (Dehghanipoodeh, Ghobadi, Baninasab, Gheysari, and Bidabadi, 2016), due to its involvement in the structural and metabolic functions of plants (Saltos, Morejón, Viera, Moran, and Gómez, 2025). Previous studies have reported positive effects on biomass production in tomato, rice, and cucumber plants (Junior, Fontes, Neves, Korndörfer, and Ávila, 2010; Marodin *et al.*, 2014). However, in this study, no significant increase in biomass production was observed. This may be related to factors such as the silicon source, plant species, and growing conditions, as indicated by Jarosz (2014).

### Yield and Physiological Variables

Yield and physiological variables showed a clear dependence on the origin of the protein hydrolysate (Table 3). The plant-based hydrolysate showed the significantly highest values ( $p \leq 0.05$ ) for fruit longitudinal diameter, individual fruit weight, total yield, and net CO<sub>2</sub> assimilation rate, although it was associated with a lower total soluble solids (TSS) content. This behavior indicates that the plant-based hydrolysate favors growth and photosynthesis but dilutes sugars in the fruits, which aligns with the inverse relationship between fruit size and TSS concentration reported by Beckles (2012). The higher yield obtained with the plant-based hydrolysate coincides with that reported by Cuevas-Cruz and Martínez (2025), who attribute this effect to the presence of carbohydrates, peptides, and phytohormones in plant hydrolysates, compounds that stimulate flowering, fruit set, and fruit growth (Matsumiya and Kubo, 2011; Ugolini *et al.*, 2015).

Likewise, the higher net CO<sub>2</sub> assimilation rate in plants treated with this hydrolysate could explain the yield increase, given that higher photosynthetic activity translates into greater availability of photoassimilates for reproductive development (Campos *et al.*, 2024). Furthermore, these hydrolysates stimulate flowering, fruit set, and fruit growth (Aguilar-Luna, Hernández, and Hernández, 2025). On the other hand, silicon did not significantly modify fruit size or yield, although the 20 mg L<sup>-1</sup> dose increased the net CO<sub>2</sub> assimilation rate. This result suggests that Si can improve photosynthetic efficiency without directly impacting productivity under the evaluated conditions. Previous studies have reported yield increases with nutrient solutions enriched with Si (Perez and Herrera, 2020), but the lack of response in this work could be due to factors such as the Si source, plant species, and growing conditions, as indicated by Jarosz (2014). No significant interaction between the type of hydrolysate and the silicon concentration was recorded for any of these variables.

**Table 3. Effect of hydrolysate source and Si concentration on total soluble solids (TSS), fruit transverse diameter, fruit longitudinal diameter, fruit weight, yield, and net CO<sub>2</sub> assimilation of grape tomato plants cv. Luciplus.**

	Fruit diameter		Fruit weight	Yield	Net CO <sub>2</sub> assimilation	Total soluble solids
	Transverse	Longitudinal				
	----- mm -----		g fruit <sup>-1</sup>	g plant <sup>-1</sup>	μmol m <sup>-2</sup> s <sup>-1</sup>	° Brix
Hydrolysate Origin						
Animal	20.7 ± 0.6 a	29.5 ± 0.8 b	6.9 ± 0.4 b	1504.7 ± 94.6 b	6.3 ± 0.5 b	11.7 ± 0.4 a
Plant	20.9 ± 0.3 a	30.4 ± 0.6 a	7.3 ± 0.4 a	1596.4 ± 106.0 a	7.5 ± 0.8 a	11.3 ± 0.5 b
Animal-Plant	20.5 ± 0.4 a	29.6 ± 0.6 b	6.9 ± 0.4 b	1524.0 ± 89.3 b	6.8 ± 0.6 b	11.4 ± 0.3 ab
Si (mg L <sup>-1</sup> )						
10	20.6 ± 0.5 a	29.6 ± 0.7 a	6.9 ± 0.4 a	1508.0 ± 84.2 a	6.6 ± 0.5 b	11.4 ± 0.4 a
15	20.8 ± 0.2 a	29.9 ± 0.7 a	7.1 ± 0.3 a	1554.3 ± 83.7 a	6.7 ± 0.9 b	11.5 ± 0.6 a
20	20.7 ± 0.5 a	29.9 ± 0.9 a	7.0 ± 0.5 a	1562.9 ± 131.5 a	7.0 ± 0.8 a	11.6 ± 0.3 a
Interaction	NS	NS	NS	NS	*	NS

Means within the same column followed by the same letter are not significantly different, according to Tukey's test ( $p \leq 0.05$ ).

## Chemical Properties of the Substrate and Leachate

The chemical properties of the substrate at the end of the cultivation cycle responded differentially to the treatments (Table 4). The origin of the hydrolysate significantly affected ( $p \leq 0.05$ ) the pH, electrical conductivity (EC), and the concentration of  $\text{NO}_3^-$ , with an increase in pH and a decrease in EC and  $\text{NO}_3^-$  concentration observed with the plant-based hydrolysate (Casbis, Torres, Rodríguez, and Nava, 2022). This behavior may be attributed to greater nutrient uptake by the plants, due to the enhanced development and yield obtained by plants treated with this hydrolysate. For its part, silicon influenced only the concentration of K, with higher values at the 10 and 20  $\text{mg L}^{-1}$  doses (Hernandez-Valencia *et al.*, 2022). The interaction between both factors was significant for EC and  $\text{NO}_3^-$ . The highest EC values were observed with the combination of the animal-plant hydrolysate and 10  $\text{mg L}^{-1}$  of Si, as well as with the animal-based hydrolysate and 15 or 20  $\text{mg L}^{-1}$  of Si (Figure 1A) (Suarez, Salcedo, and Zapata, 2022). The maximum  $\text{NO}_3^-$  concentration occurred with the animal-plant hydrolysate combined with 15  $\text{mg L}^{-1}$  of Si (Figure 1B).

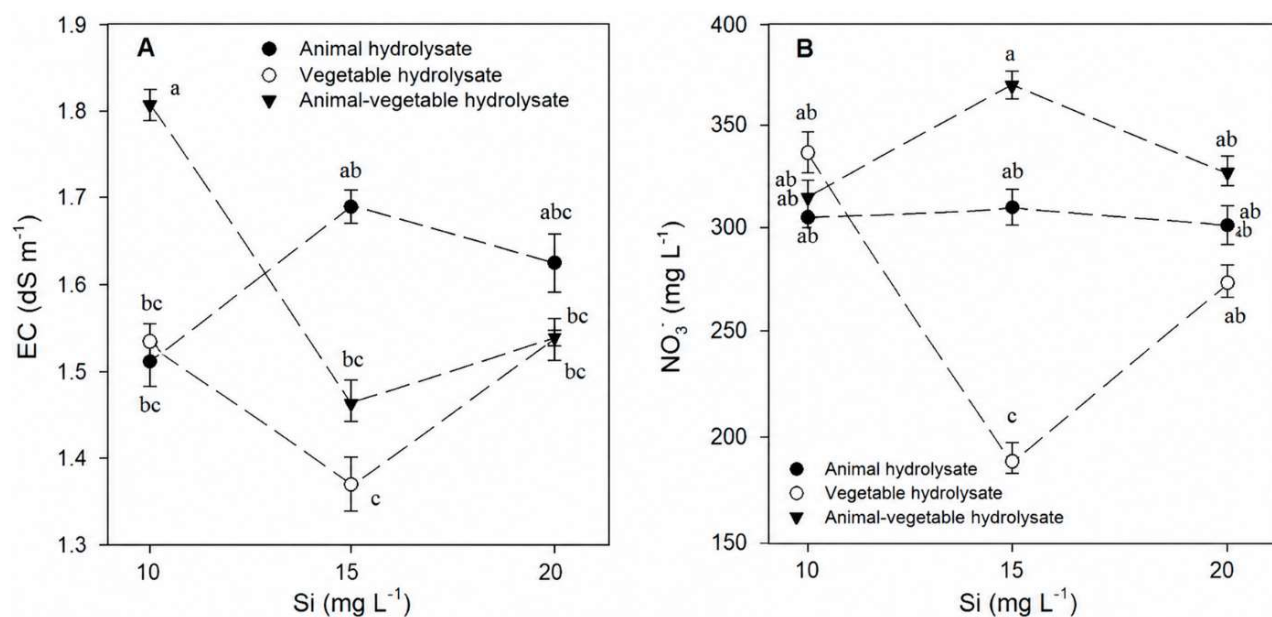
This behavior aligns with the hypothesis that hydrolysates can improve the availability and uptake of nutrients through mechanisms such as nutrient complexation by peptides and amino acids, stimulation of root development, and enhanced microbial activity (du Jardin, 2015; Tejada-Vizcarra *et al.*, 2025; Galindo, González, Marrero, Rodríguez, and Herrera, 2025). Regarding silicon, although it has been reported that it can modify nutrient uptake by increasing P, Ca, and Mg and reducing N and K (Liang, Sun, Zhu y Christie, 2007; Torres-Rodríguez, Ramos, Reyes, Quinatoa, and Rivas, 2024), in this study the 15  $\text{mg L}^{-1}$  dose reduced the concentration of  $\text{NO}_3^-$  and K in the substrate without affecting growth or yield, suggesting that its influence depends on the species, source, and growing conditions.

The leachate showed a pattern similar to the substrate for pH, EC, and  $\text{NO}_3^-$  content. The pH was consistently higher in treatments with the plant-based hydrolysate for most of the cycle, decreasing around 60 days after transplanting (Figures 2A-C). The EC showed a cumulative trend in all treatments, although the increase was less pronounced with the plant-based hydrolysate (Figures 2D-F). This pattern suggests greater nutrient uptake in plants treated with the plant-based hydrolysate, which coincides with their greater development and yield. This could be due to the ability of hydrolysates to improve nutrient availability and uptake by plants through various mechanisms such as nutrient complexation by peptides and amino acids, improved root development, and enhanced microbial activity (Cerdán *et al.*, 2009; du Jardin, 2015; Martínez-Gutierrez *et al.*, 2022). However, further studies are needed to evaluate nutrient uptake by the plant and the behavior of nutrients in the growing medium when protein hydrolysates are added to the nutrient solution. The nutrient dynamics in the leachate presented a common pattern for  $\text{NO}_3^-$  and K, regardless of the applied treatment (Figure 3). For both ions, the concentration showed an initial increase from day 3 to 60 days after transplanting (DAT). Subsequently, a decrease phase was recorded between 60 and 90 DAT, followed by a recovery trend that extended until the end of the cycle (150 DAT) (Figures 3A-F). Regarding Si, it has been indicated that the application of Si in plant nutrition affects plant nutrient uptake and can improve the absorption of P, Ca, and Mg or decrease the absorption of N and K (Anchondo-Páez *et al.*, 2024). In this study, the 15  $\text{mg L}^{-1}$  Si dose reduced the concentration of  $\text{NO}_3^-$  and K in the substrate without affecting plant growth or yield.

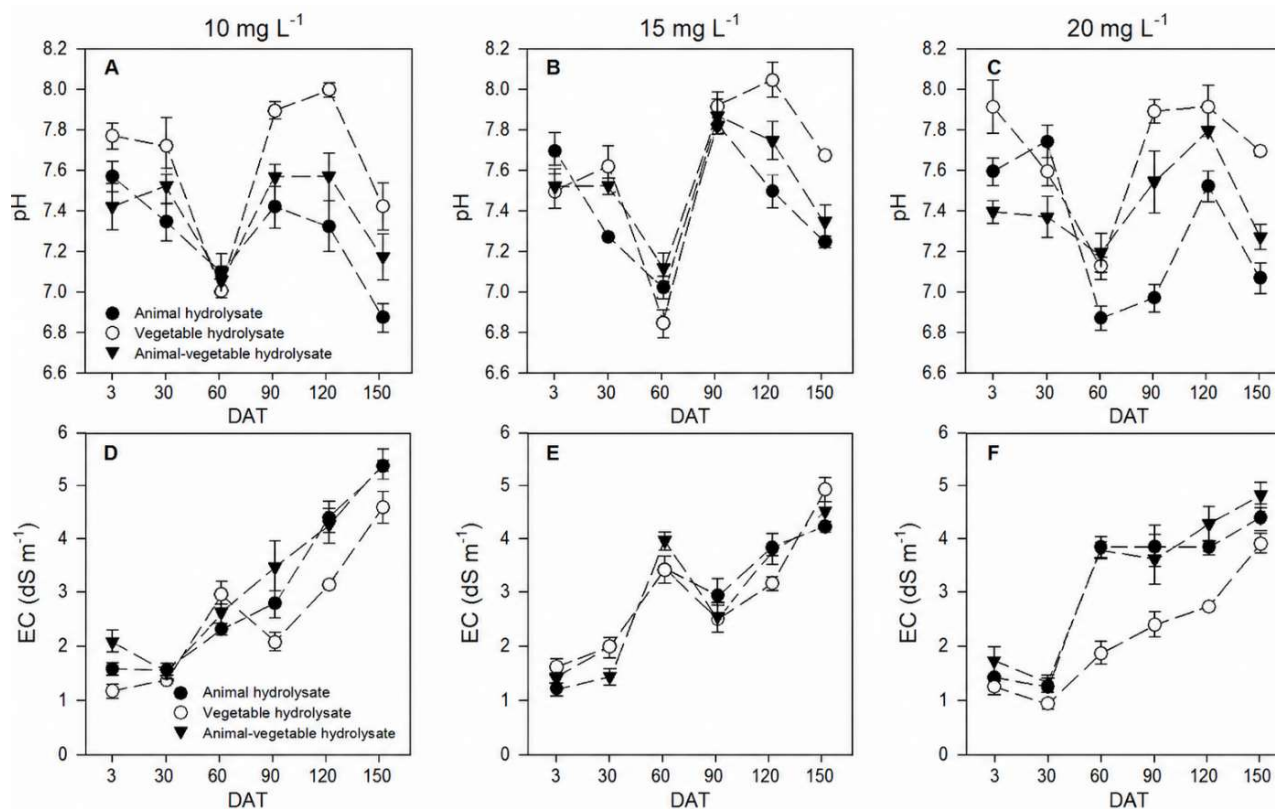
**Table 4. Effect of hydrolysate source and Si concentration on pH, EC, and concentration of  $\text{NO}_3^-$  and K in the substrate at the end of the cultivation cycle of grape tomato plants cv. Luciflus.**

	pH	CE	$\text{NO}_3^-$	K
		$\text{dS m}^{-1}$	----- $\text{mg L}^{-1}$ -----	
Hydrolysate Origin				
Animal	6.04 ± 0.1 b	1.61 ± 0.1 a	306.7 ± 28.9 a	25.83 ± 3.9 a
Plant	6.42 ± 0.2 a	1.47 ± 0.1 b	268.6 ± 65.3 b	23.07 ± 5.3 a
Animal-Plant	6.05 ± 0.1 b	1.62 ± 0.2 a	335.65 ± 32.8 a	26.94 ± 8.4 a
Si ( $\text{mg L}^{-1}$ )				
10	6.2 ± 0.2 a	1.60 ± 0.2 a	318.2 ± 28.4 a	29.99 ± 6.4 a
15	6.2 ± 0.3 a	1.53 ± 0.2 a	290.4 ± 79.2 a	20.11 ± 3.6 b
20	6.1 ± 0.2 a	1.56 ± 0.1 a	302.3 ± 33.9 a	25.75 ± 3.9 a
Interaction	NS	*	*	NS

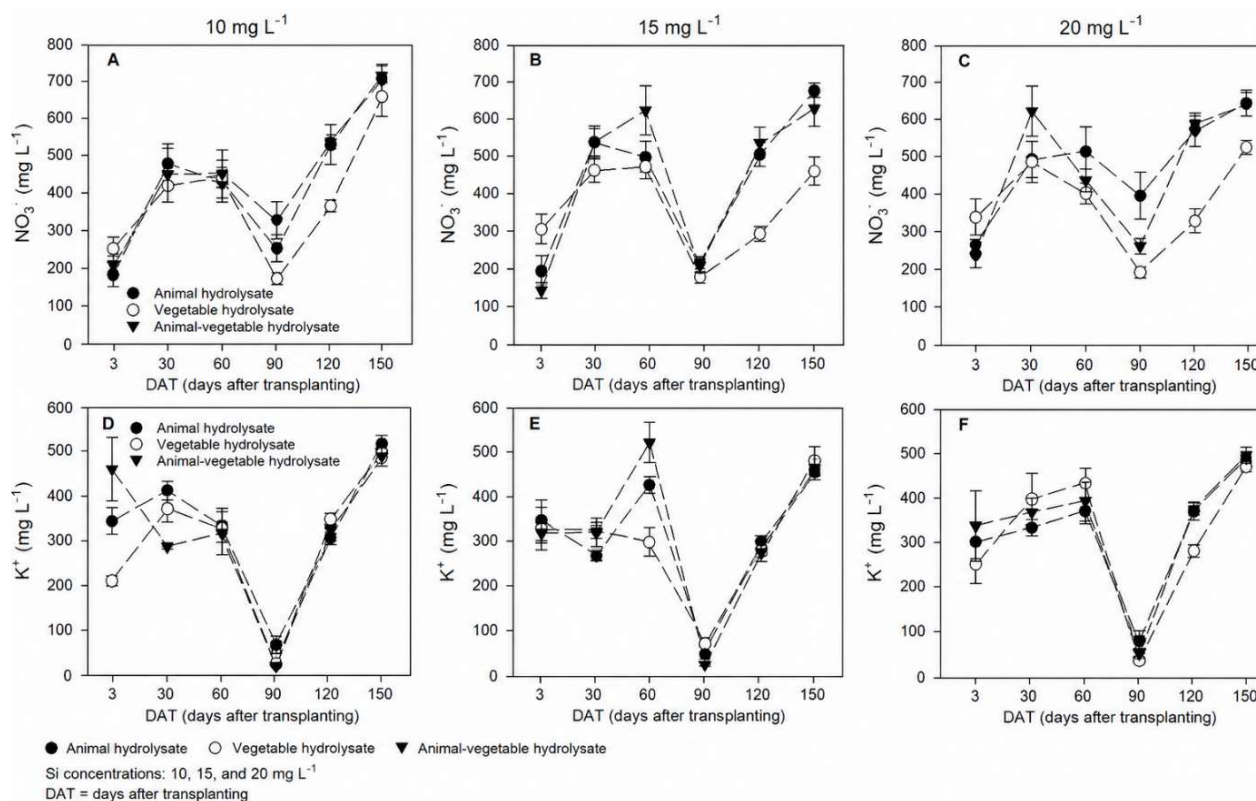
Means within the same column followed by the same letter are not significantly different, according to Tukey's test ( $p \leq 0.05$ ).



**Figure 1.** Behavior of EC and NO<sub>3</sub><sup>-</sup> in the substrate at the end of the cultivation cycle of grape tomato plants *cv. Lucifus* was subjected to different hydrolysate sources and Si concentrations. Bars represent the standard error of the mean.



**Figure 2.** Behavior of pH and EC in the leachate as a function of the protein hydrolysate origin and Si concentration applied to grape tomato plants *cv. Lucifus*. DAT = days after transplanting. Bars represent the standard error of the mean.



**Figure 3. Behavior of  $\text{NO}_3^-$  and  $\text{K}^+$  in the leachate as a function of the protein hydrolysate origin and applied Si concentration in tomato plants cv. Luciflus. DAT = days after transplanting. Bars represent the standard error of the mean.**

## CONCLUSIONS

The origin of the protein hydrolysate significantly influenced growth, yield, and the chemical properties of the substrate and leachate in grape tomato plants, with the plant-based hydrolysate standing out for enhancing shoot biomass, yield, and nutrient uptake, as reflected by lower  $\text{NO}_3^-$  concentrations and electrical conductivity and a higher pH. Silicon application did not significantly affect biomass or yield; however, the 20  $\text{mg L}^{-1}$  dose improved photosynthetic efficiency, and the 15  $\text{mg L}^{-1}$  dose reduced  $\text{NO}_3^-$  and K concentrations in the substrate without affecting plant development. Overall, these results indicate that plant-derived hydrolysates represent an effective strategy to improve crop productivity, while silicon may contribute to optimizing physiological and nutritional processes under specific conditions, but is not a determining factor for yield.

## ETHICS STATEMENT

Not applicable.

## CONSENT FOR PUBLICATION

Not applicable.

## AVAILABILITY OF SUPPORTING DATA

The data used and analyzed in this study can be sent upon formal request by the interested party to the corresponding author.

## COMPETING INTERESTS

The authors declare that there are no conflicts of interest related to this article.

## FINANCING

Not applicable.

## AUTHORS' CONTRIBUTIONS

Conceptualization: C.J.L.C., P.P.R. and J.C.G.S.; formal analysis: A.Z.G. and T.R.G.; investigation: J.C.G.S. and D.A.Z.G.; methodology: C.J.L.C. and A.Z.G.; project administration: P.P.R. and C.J.L.C.; supervision: P.P.R. and A.Z.G.; validation: T.R.G.; visualization: D.A.Z.G.; writing – original draft preparation: C.J.L.C., J.C.G.S. and A.Z.G.; writing – review and editing: P.P.R. All authors read and approved the final manuscript.

## ACKNOWLEDGMENTS

Not applicable.

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