Ecosist. Recur. Agropec. Núm. Esp. VI: e5128, 2026
https://doi.org/10.19136/era.a13nVI.5128

Nutraceutical properties in Jalapeño pepper biostimulated with Arbuscular Mycorrhizal Fungi and Plant Growth Promoting Rhizobacteria

Propiedades nutracéuticas en chile Jalapeño bioestimulado con Hongos Micorrízicos Arbusculares y Rizobacterias Promotoras del Crecimiento Vegetal

Patricia Vázquez-López[1], María Esther Ríos-Vega[1], Sandra Iliana Torres-Herrera[2], Ernesto Concilco-Alberto[1], Rigoberto González-Mancillas[3], Apolinar González-Mancilla[1*]

[1]Agriculture and Zootechnics Faculty, Juarez University of the State of Durango. CP. 35170. Gomez Palacio-Tlahualilo highway km 32, Venecia Gomez Palacio, Durango, México.
[2]Forestry and Environmental Sciences Faculty, Juarez University of the State of Durango. Boulevard Durango, corner with Papaloapan river s/n, CP. 35120. Durango. Durango, México.
[3]National Technological Institute of Mexico/Papaloapan Basin Technological Institute. Av. Technological No. 21. CP. 68446. San Bartolo Tuxtepec, Oaxaca.

*Corresponding author: apolinar.gonzalez@ujed.mx

Scientific article

Received: March 05, 2026
Accepted: August 11, 2026

ABSTRACT. The use of biofertilizers formulated with Plant Growth Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF) represents a sustainable and viable option for optimizing the growth and yield of jalapeño pepper (*Capsicum annuum* L.). The objective of this work was to evaluate two AMF consortia and two PGPR on the growth and yield of jalapeño pepper grown in a greenhouse. A completely randomized experiment was established with five treatments and ten replicates: AMF1 (*Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum*, and *Diversispora spurca*), AMF2 (*C. etunicatum*, *C. claroideum*, and *G. postulatum*), AC35 (*Serratia liquefaciens*), and PC35 (*Serratia plymuthica*), compared to a control. The variables measured were height, leaf area, fruit weight and size, flavonoids, phenols, antioxidant capacity, vitamin C, total protein, and capsaicin. The results indicated that jalapeño pepper growth (height and leaf area) and fruit size (length, diameter, and width) were better in the treatments with AMF1 and AMF2. The amount of flavonoids (225.8 mg QE per 100 g of fruit) and antioxidant capacity (69 mEq Trolox per 100 g of fruit) were higher when the plants were inoculated with AMF2; total protein (0.025 mg g^{-1}) was higher with AMF1. Plants inoculated with the rhizobacteria AC35 and PC35 showed outstanding total phenols (473.8 mg GAE per 100 g of fruit) and capsaicin (0.60 mg g^{-1}), respectively. Biofertilizers are sustainable and viable alternatives for improving growth and nutraceutical properties in jalapeño pepper cultivation.
Keywords: *Capsicum annuum L.*, flavonoids, vitamin C, capsaicin, glomus.

RESUMEN. El uso de biofertilizantes formulados con Rizobacterias Promotoras del Crecimiento Vegetal (PGPR) y Hongos Micorrízicos Arbusculares (AMF), representa una opción sostenibles y viables para optimizar el crecimiento y rendimiento del chile jalapeño (*Capsicum annuum* L.). El objetivo de este trabajo fue evaluar dos consorcios de AMF y dos cepas de PGPR en el crecimiento y rendimiento del chile jalapeño cultivado en invernadero. Se estableció un experimento completamente al azar con 5 tratamientos y diez repeticiones: AMF1 (*Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* y *Diversispora spurca*), AMF2 (*C. etunicatum*, *C. claroideum* y *G. postulatum*), AC35 (*Serratia liquefaciens*) y PC35 (*Serratia plymuthica*), comparados con un testigo. Las variables medidas fueron altura, área foliar, peso y tamaño de frutos, flavonoides, fenoles, capacidad antioxidante, vitamina C, proteína total y capsaicina. Los resultados indicaron que el crecimiento de chile jalapeño (altura y área foliar) y el tamaño de frutos (largo, diámetro y ancho) fueron mejores en los tratamientos con AMF1 y AMF2. La cantidad de flavonoides (225.8 mg QE en 100 g de fruto) y la capacidad antioxidante (69 mEq Trolox en 100 g de fruto) fueron más altos cuando las plantas se inocularon con el AMF2; la proteína total (0.025 mg g^{-1}) fue mayor con el AMF1. Las plantas inoculadas con las rizobacterias AC35 y PC35 fueron sobresalientes en fenoles totales (473.8 mg de GAE en 100 g de fruto) y capsaicina (0.60 mg g^{-1}), respectivamente. Los biofertilizantes, son alternativas sustentables y viables para mejorar el crecimiento y las propiedades nutracéuticas en el cultivo de chile jalapeño.
Palabras clave: *Capsicum annuum L.*, flavonoides, vitamina C, capsaicina, glomus.

How to cite: Vázquez-López P, Ríos-Vega ME, Torres-Herrera SI, Ernesto Concilco-Alberto E, González-Mancillas R, Apolinar González-Mancilla A (2026) Nutraceutical properties in Jalapeño pepper biostimulated with Arbuscular Mycorrhizal Fungi and Plant Growth Promoting Rhizobacteria. Ecosistemas y Recursos Agropecuarios Núm. Esp. VI: e5128. DOI: 10.19136/era.a13nVI.5128.

Ecosist. Recur. Agropec. Núm. Esp. VI: e5128, 2026
https://doi.org/10.19136/era.a13nVI.5128

INTRODUCTION

Chili pepper is a solanaceous crop cultivated worldwide. In 2024 Mexico ranked third in production with more than 3.2 million tons, surpassed by China and India, which in that same year produced more than 17.3 and 5.3 million tons (FAOSTAT 2026). The importance of this crop lies in the multiple benefits it offers to the digestive and immune systems, particularly due to the nutraceuticals found in the fruit, such as ascorbic acid (vitamin C), flavonoids, phenols, antioxidants, and capsaicin (Kumar and Tata 2009, Sánchez *et al*. 2022, Faliarizao *et al*. 2025, Akter *et al*. 2026, Zhou *et al*. 2026). In Mexico, it has multiple uses, including food, medicine, cosmetics and ornamental purposes (Ravishankar *et al*. 2003).

Nationally, the jalapeño pepper is the most economically important crop. In 2023, there was a planted area of 30 223 ha, which generated a production volume of 909 225 tons of green fruit, generating an economic value of more than 8 058 million pesos (SIAP-SIACON 2024). Jalapeño peppers are grown in 25 states of the Mexican Republic. Of these, Chihuahua ranked first in production with 383 423 tons, produced on 11 154 ha, with an economic value of 3 097 million pesos; in the same year, the state of Durango produced 14 670 tons from 407 ha of cultivated area, with an economic yield of 95 million pesos (SIAP-SIACON 2024).

The factors limiting the production of this crop include pests and diseases (Pérez *et al*. 2017, Hernández *et al*. 2021), low soil fertility, and limited government support. These issues lead to reduced production, economic losses, and a lack of interest in continuing to cultivate the crop (Sánchez-Toledano *et al*. 2021). The above factors are controlled through the use of industrial chemicals, which can contaminate water, soil, plants and, human health. The use of Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth-Promoting Rhizobacteria (PGPR) as sustainable biostimulants enhances the growth, yield, and nutraceutical properties of treated crops; these microorganisms can be isolated, selected, and inoculated to promote plant growth.

Favorable results with AMF and PGPR have been demonstrated in jalapeño pepper crops with *Serratia liquefaciens* and *S. plymuthica* (Camacho-Rodríguez *et al*. 2022) and with *Pseudomonas tolaasii*, *Bacillus pumilus* and consortia of *Funneliformis geosporum* and *Claroideoglomus* (Angulo-Castro *et al*. 2018). In poblano peppers with the joint inoculation of *F. geosporum*, *Claroideoglomus* sp., and *P. tolaasii*, or with *F. geosporum*, *Claroideoglomus* sp., and *S. plymuthica* (González-Mancilla *et al*. 2024), or with joint or separate biofertilization with *F. geosporum*, *Claroideoglomus* sp., *C. etunicatum*, and *Arthrobacter* sp. (Almaraz-Suárez *et al*. 2021, Almaraz-Suárez *et al*. 2022). The results found were greater growth (height, leaf area, leaves, branches, and dry biomass); higher yield (flowers and fruits); and greater photosynthetic efficiency in inoculated plants. The objective of this study was to evaluate consortia of Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth Promoting Rhizobacteria (PGPR) on the growth, yield and nutraceutical characteristics of jalapeño pepper grown in greenhouses.

MATERIALS AND METHODS

Preparation of microbial inoculum

Two strains of PGPR from the rhizosphere soil of poblano pepper crops in Puebla, Mexico, were used. *Serratia plymuthica* (with accession number GenBank KX259564) solubilizes phosphorus (744 μg mL^{-1}) and inhibits the growth of *Phytophthora capsici* (42%) and *Fusarium* sp. (37%). *Serratia liquefaciens* (with accession number GenBank KX259559) produces auxins (23.9 g mL^{-1}), inhibits the growth of *Phytophthora capsici* (34.5%) and *Fusarium* sp. (39.4%), respectively (González *et al*. 2017). For the reactivation of the strains, solid nutrient agar medium was poured into Petri dishes, solidified, labeled and the strains were seeded, then incubated for two days at 28°C. After reactivation, a liquid biofertilizer was prepared in a nutrient broth medium. The bacteria were taken with a bacterial loop and transferred to the previously sterilized broth, which was stirred constantly at room temperature for two weeks until a growth of 10^7 CFU mL^{-1}.

The AMF were collected from jalapeño pepper crops in the municipality of Francisco I Madero, Coahuila, Mexico. Two AMF consortia were used [AMF1 consisting of *Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* and *Diversispora spurca*; AMF2 consisting of *C. etunicatum*, *C. claroideum* and *G. postulatum*]. The AMF were propagated in trap culture for spore reproduction and conservation for six months, after which they were quantified by wet sieving and decanting, expressed in 100 g of dry soil for spore extraction (Gerdemann and Nicolson 1963) and purified by removing organic matter using the sucrose gradient flotation method with 100 g of dry soil (Sieverding 1983). The inoculum contained a total of 243 and 203 spores per 100 g of dry soil for consortia AMF1 and AMF2, respectively.

Establishment and experimental design

Jalapeño pepper seeds were sown in 200-cell polystyrene trays; prior to sowing, the seeds were disinfected with 1% chlorine and washed three times with distilled water. A previously sterilized mixture of peat moss, perlite, and vermiculite (1:1:1) was used as the substrate. Arbuscular mycorrhizal fungi (AMF) were inoculated before sowing, using a mixture of 50% mycorrhizal inoculum and 50% substrate. The PGPR were inoculated five days after germination, using 1 mL per seedling. The seedlings were transplanted 60 days after sowing in seed trays, directly into the soil under a greenhouse using drip irrigation. A completely randomized design was established, testing five treatments: two based on AMF [AMF1 (*Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* and *Diversispora spurca*), and AMF2 (*C. etunicatum*, *C. claroideum* and *G. postulatum*)], two with PGPR [AC35 (*Serratia liquefaciens*) and PC35 (*Serratia plymuthica*)], and a control treatment without microorganisms (T).

Fifty repetitions were established per treatment; however, only 10 repetitions were evaluated for each one. The soil where it was transplanted had a moderately alkaline pH (8.4) (soil: water, 1:2), organic matter content of 2.2%, inorganic nitrogen of 61.5 mg kg^{-1} interpreted as very high, and available phosphorus of 20.2 mg kg^{-1}; the texture was clay loam. The initial height of seedlings at the time of transplanting was 6.0 (AMF1), 4.9 (AMF2), 6.3 (AC35), 7.2 (PC35), and 5.4 (T) cm per plant.

Variables evaluated

The variables evaluated as indicators of growth, yield, and nutraceutical properties were height, leaf area, number of fruits, fruit length, width and weight, flavonoid content, total phenols, antioxidant capacity, vitamin C, total protein, and capsaicin. Height was determined using a ruler graduated in centimeters, and leaf area was measured with a leaf area meter (LI-COR, LI-3100) by separating the leaves from the branches. The number of fruits was quantified visually and size (length and diameter) was determined with an electric vernier caliper graduated in mm. Weight was obtained by weighing each fruit on a precision analytical balance (AdventurePro).

The nutraceutical properties in jalapeño pepper were obtained by processing fully developed fruits. To do this, 2 g of extract from fresh samples were mixed in 10 ml of 80% ethanol; it was subjected to constant orbital agitation for 24 h at 70 rpm and 5°C. The resulting extracts were centrifuged at 3000 rpm for 5 min for subsequent analysis (Salas-Pérez *et al*. 2016). Flavonoids were determined by a colorimetric method; 250 µL of ethanolic extract was taken and mixed with 1.25 ml of distilled water and 75 µL of $NaNO_2$ (5%). The sample was allowed to stand for 5 min; 150 µL of AlCl3 (aluminum chloride-1-ethyl-3-methylimidazolium chloride; Sigma-Aldrich, St. Louis, MO, USA), 500 µL of NaOH (1 M), and 275 µL of distilled water were added. Finally, the samples were shaken vigorously, and readings were taken using a Uv-Vis optical detector at 510 nm. To generate the calibration curve, a standard sample of quercetin dissolved in absolute ethanol was prepared; the results were expressed as mg of quercetin per 100 g of fresh weight.

Phenols were determined using a modification of the Folin-Ciocalteu method. (Singleton 1999). For this purpose, 50 µL of the ethanolic extract diluted in 3 mL of distilled water was used; 250 µL of Folin-Ciocalteau reagent (1N) was added, and the mixture was shaken and allowed to react for 3 min. 750 µL of Na2CO3 (20%) and 950 µL of distilled water were added; the mixture was allowed to stand for 2 h, and the reading was taken using an optical detector (Uv-Vis) at 760 nm. A calibration curve was prepared using gallic acid, and the results were expressed as mg of gallic acid equivalents (GAE) per 100 g of fresh weight.

Fruit antioxidant capacity was quantified using the in vitro DPPH+ method (Brand-Williams *et al*. 1995). To this end, 50 µL of sample and 950 µL of methanolic DPPH+ solution were mixed; after a 30-minute reaction period, absorbance was measured at 517 nm using an optical detector (Uv-Vis). Measurements were performed in triplicate using ethanol as a blank. A standard curve was prepared using Trolox (Aldrich, St. Louis, Missouri, USA), and results were reported as Trolox milliequivalents per 100 g of fresh weight (mEq Trolox 100 g FW^{-1}).

Vitamin C (ascorbic acid) content in fresh fruit was quantified using the HPLC technique described by Doner and Hicks (1981). Jalapeño peppers were chopped, and a 10 g sample was blended with 20 mL of an extraction mixture in a kitchen blender; the sample was then homogenized and filtered for analysis. A calibration curve was prepared using ascorbic acid, and detection was performed at 268 nm (Uv-Vis); results were expressed in mg per 100 g of fresh weight.

Total protein content was evaluated using the bicinchoninic acid (BCA) technique (Smith *et al*. 1985). A 25 µL aliquot of the homogenate was taken and digested in 500 µL of 0.1 N NaOH for 120 minutes; 25 µL of the digest was taken and placed in a microplate, the BCA reagent was added, and it was incubated at 60 °C for 15 minutes. Finally, the samples were read in the Uv-Vis optical detector at 760 nm. Capsaicin content in the fruit was quantified using the modified method of Cisneros-Pineda *et al*. (2007); a standard curve for capsaicin and dihydrocapsaicin (Sigma) was prepared, and readings were taken at 273 nm using a Uv-Vis optical detector. Results were expressed as mg of capsaicin per g of dry sample.

Statistical analysis

Data were recorded in Excel, and the means and standard deviation were calculated. Statistical analysis was performed using SAS 2002 software, obtaining an analysis of variance and Tukey´s multiple comparison test ($p \leq 0.05$).

RESULTS

Growth and yield of jalapeño pepper

The results of inoculation with Plant Growth Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF) on the growth of jalapeño pepper showed statistically significant differences in each of the treatments (Table 1) (Tukey, $p \leq 0.05$). The final plant height was higher in the AMF2 and AMF1 treatments with AMF2 and AMF1, which averaged 81 and 77 cm in height, respectively. The lowest height was found in plants treated with PGPR PC35 (60 cm), while the control averaged 69 cm in height. The AMF2 treatment showed a 17.3% increase in height compared to the control.

Table 1. Final height (FH), number of leaves (NL), leaf area (FA) and chlorophyll content index (CCI) in jalapeño pepper plants biofertilized with AMF and PGPR, 96 DAT.

Treatment	FH (cm)	NL	FA (cm^2)	Chlorophyll (CCI)
AMF1	77^{a}	36^{ab}	4826^{a}	46.5^{a}
AMF2	81^{b}	35^{ab}	3754^{ab}	45.9^{a}
AC35	70^{c}	41^{a}	2788^{bc}	34.2^{b}
PC35	60^{c}	30^{ab}	2371^{c}	35.1^{b}
T	69^{c}	24^{b}	2933^{bc}	31.2^{b}

AMF1 = *Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* and *Diversispora spurca*; AMF2 = *C. etunicatum*, *C. claroideum* and *G. postulatum*; AC35 = *Serratia liquefaciens*; PC35 = *Serratia plymuthica*. T = control. Different letters within the columns indicate statistically significant differences ($p \leq 0.05$). n = 10. ± E.E.

The plants treated with AC35 had the highest number of leaves (41 leaves), followed by the AMF1 treatment (36 leaves); the lowest value was presented by the T treatment (24 leaves). The AC35 treatment showed a 70.8% increase in the number of leaves compared to the plants without microbial inoculation (control). At the end of the experiment, the leaf area was higher in plants inoculated with AMF1, with an average leaf area of 4826 cm^2, followed by the AMF2 treatment with 3 754 cm^2; the lowest value was presented by the PC35 treatment with an average of 2371 cm^2, while the control obtained 2933 cm^2 of leaf area. The AMF1 treatment showed a 64. 5% increase in

Ecosist. Recur. Agropec. Núm. Esp. VI: e5128, 2026
https://doi.org/10.19136/era.a13nVI.5128

leaf area compared to the control. The chlorophyll content index (CCI) was better in plants treated with AMF1 and AMF2, both with 46.5 and 45.9 CCI (Table 1).

The number of fruits was higher in plants inoculated with AMF1 which produced an average of 27 fruits, while the AMF2 treatment yielded an average of 16 fruits per plant; plants without inoculation (control) produced 11 fruits. The best treatment showed a 145.4% increase in the number of fruits compared to the control. Fruit length was higher in the AMF1 treatment, which had 80.9 mm. Below this treatment was the AC35 treatment with 80.6 mm in length, while the lowest value, 74.7 mm was obtained with PC35 inoculation. The control obtained 75.7 mm in length, and the AMF1 treatment showed a 6.8% increase in fruit length compared to the control (Table 2).

Table 2. Number and size of jalapeño pepper fruits (length, diameter, and weight) biofertilized with AMF and PGPR, 96 DAT.

Treatment	Fruits	Length (mm)	Diameter (mm)	Weight (g)
AMF1	27[a]	80.9[a]	33.5[a]	32.6[a]
AMF2	16[b]	77.7[a]	33.4[a]	31.4[a]
AC35	10[c]	80.6[a]	30.4[ab]	23.7[b]
PC35	9[c]	74.7[a]	32.3[ab]	27.7[ab]
T	11[c]	75.7[a]	29.5[b]	23.5[b]

AMF1 = *Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* and *Diversispora spurca*; AMF2 = *C. etunicatum*, *C. claroideum* and *G. postulatum*; AC35 = *Serratia liquefaciens*; PC35 = *Serratia plymuthica*. T = control. Different letters within the columns, indicate statistically significant differences ($p \leq 0.05$). n = 10. ± E.E.

In the case of fruit diameter, we observed that treatment AMF1 obtained better results with 33.5 mm, followed by AMF2 with 33.4 mm; the lowest value was found in the control, which averaged 29.5 mm. The AMF1 treatment showed a 13.5% increase in fruit diameter compared to the plants without inoculation (control). In terms of individual fruit weight, the best data was collected in the AMF1 treatment, which obtained 32.6 g, followed by the AMF2 treatment with 31.4 g; the lowest fruit weight was found in plants without microbial inoculation (control), which averaged 23.5 g per fruit; the AMF1 treatment showed a 38.7% increase in fruit weight compared to the control plants (Table 2).

Nutraceutical properties in jalapeño pepper

The nutraceutical properties of jalapeño pepper fruits showed statistically significant differences (Tukey, $p \leq 0.05$) depending on microbial inoculation. The amount of flavonoids was higher in plants biofertilized with AMF2, which had an average of 225.8 mg QE 100 g PF^{-1}, while the lowest value was found in fruits obtained from plants treated with PC35 with 144.4 mg QE 100 g PF^{-1}. The highest amount of phenols in fruits was found in the AC35 treatment, which obtained 473.8 mg GAE 100 g PF^{-1}, while the lowest value was found in the PC35 treatment with 272.9 mg GAE 100 g PF^{-1}. The control presented an amount of 435.0 mg GAE 100 g PF^{-1}. Regarding antioxidant capacity, the highest result was obtained with treatment AMF2 with 69.0 mEq TROLOX 100 g PF^{-1}, and the lowest amount of antioxidants was found in fruits from treatment AC35 with 47.9 mEq TROLOX 100 g PF^{-1} (Table 3).

Ecosist. Recur. Agropec. Núm. Esp. VI: e5128, 2026
https://doi.org/10.19136/era.a13nVI.5128

Table 3. Nutraceutical characteristics in jalapeño pepper biofertilized with AMF and PGPR, 96 DAT.

Treatments	Flavonoids	Total phenols	Antioxidant capacity	Vitamin C	Total protein	Capsaicin
	(mg QE 100 g PF^{-1})	(mg GAE 100 g PF^{-1})	(mEq Trolox 100 g PF^{-1})	(mg 100 g PF^{-1})	(mg g^{-1})	(mg g^{-1})
AMF1	178.2^{b}	370.2^{b}	56.9^{b}	66.0^{b}	0.025^{a}	0.59^{c}
AMF2	225.8^{a}	467.2^{a}	69.0^{a}	80.7^{ab}	0.007^{d}	0.57^{d}
AC35	181.3^{b}	473.8^{a}	47.9^{c}	66.0^{b}	0.006^{e}	0.62^{a}
PC35	144.4^{c}	272.9^{c}	48.1^{c}	73.3^{ab}	0.013^{b}	0.60^{b}
T	184.9^{b}	435.0^{ab}	67.0^{a}	88.3^{a}	0.010^{c}	0.30^{e}

AMF1 = *Claroideoglomus claroideum, C. etunicatum, Glomus postulatum and Diversispora spurca*; AMF2 = *C. etunicatum, C. claroideum and G. postulatum*; AC35 = *Serratia liquefaciens*; PC35 = *Serratia plymuthica.* QE = Quercetin Equivalent, PF = Fruit weight, GAE = Galic acid, Trolox = analog of vitamin E. T = control. Different letters within the columns, indicate statistically significant differences (Tukey, $p \leq 0.05$). n = 10. ± E.E.

The results for vitamin C content in jalapeño pepper ranged from 88.3 to 66.0 mg 100 g PF^{-1}; the highest value was found in the control group with 88.3 mg 100 g PF^{-1}, followed by the AMF2 treatment with 80.7 mg 100 g PF^{-1}. The highest total protein value was found in the AMF1 treatment with 0.025 mg g^{-1}, the AC35 strain obtained the lowest value with 0.006 mg g^{-1}, and the fruits of the plants without inoculation (control) presented an average of 0.010 mg g^{-1}. The content of capsaicin defines the degree of pungency of this fruit, the highest capsaicin value was found in fruits from plants subjected to the AC35 treatment at 0.62 mg g^{-1}, followed by the PC35 treatment at 0.60 mg g^{-1}. The fruits of the control treatment had the lowest pungency with 0.30 mg g^{-1} of capsaicin (Table 3).

DISCUSSION

Growth and yield of jalapeño pepper

Several studies have demonstrated plant growth when inoculated with Arbuscular Mycorrhizal Fungi and Plant Growth Promoting Rhizobacteria. For example, González-Mancilla *et al*. (2024) reported that the AMF consortia formed are *Funneliformis geosporum* + *Claroidoglomus* sp., combined with the PGPR *Rhizobium nepotum*, *Serratia plymuthica*, or *Pseudomonas tolaasii*, can generate a greater number of leaves (29.5), leaf area (209 cm^2), greater height, greater dry biomass (1 452 g), and greater phosphorus content in plants (5.6 g $planta^{-1}$) of poblano pepper. When *Funneliformis geosporum* + *Claroideoglomus* spp. + *Arthrobacter* sp. are inoculated in poblano pepper, plant height, number of leaves, leaf area, mycorrhizal colonization, and dry biomass production are improved; the increases in height, number of leaves, leaf area, and dry biomass were 113, 68, 264 and 227% compared to the control (Almaraz-Suárez *et al*. 2022). In this study, AMF1 increased plant height and leaf area by 17.3 and 64.5% respectively, while strain AC35 increased the number of leaves and flowers per plant by 70.8 and 140%, respectively.

On the other hand, the positive effects on plant growth and yield are possibly related to the ability of PGPR and AMF to improve the photochemical efficiency of photosystem II (PSII) as mentioned by Almaraz-Suárez *et al*. (2022); the joint inoculation of these microorganisms can improve the photosynthetic activity of plants, which includes transpiration, internal CO_2 concentration, stomatal conductance and photosynthesis rate (González-Mancilla *et al*. 2024). In the case of PGPR, their positive effects are also due to their ability to fix atmospheric nitrogen, solubilize phosphorus, produce auxins and inhibit the development of phytopathogens (González *et al*. 2017). Finally, in AMF, their positive effects are due to their ability to promote the transport of nutrients (nitrogen and phosphorus) and water to plant roots (Almaraz-Suárez *et al*. 2021). Inoculation of jalapeño pepper with *Serratia plymuthica* and *S. liquefaciens* in pots resulted in a higher number of fruits (3 and 5.3), length (60 and 62 mm), and diameter (24 and 21 mm) compared to plants without microorganisms (Camacho-Rodríguez *et al*. 2022); these values were lower than the results found in this study, but under greenhouse conditions and transplanted into soil.

Nutraceutical properties in jalapeño pepper

Several studies have demonstrated the positive effects on the nutraceutical characteristics of Capsicum varieties when they are biofertilized with PGPR and AMF. Tahmasebi *et al*. (2023) inoculated various PGPR (*Bacillus subtilis*, *Azospirillum* sp., and *Pseudomonas* sp.) into bell pepper plants and found an increase in total phenol content (85-93 mg GAE 100 PF^{-1} compared to chemical fertilization (70-80 mg GAE 100 PF^{-1}). They also observed increases in the antioxidant activity of the fruits (66%) compared to chemical fertilization (58%).

When inoculating AMF (*Rhizophagus irregularis* + *Funneliformis mosseae*) and three PGPR consortia (*Azotobacter chroococcum* + *Azospirillum lipoferum*, *Bacillus subtilis* + *B. amyloliquefaciens*, and *Enterobacter cloacae* + *Pseudomonas putida*) into bell pepper plants, they found higher total phenol content (between 30 and 33 mg g PF^{-1}) and ascorbic acid (vitamin C, between 112.5 and 120 mg g PF^{-1}) compared to the amount of phenols (27.5 mg g PF^{-1}) and ascorbic acid (105 mg g PF^{-1}) found in plants without microbial inoculation (control) (Sini *et al*. 2024). In another study with *Glomus mosseae* in chili plants (*C. annuum* L. Sina F1), higher amounts of capsaicin (139.2 μg g^{-1}) and vitamin C (100.2 μg 100 g^{-1}) compared to plants without mycorrhizae (control), which had 133.3 μg g^{-1} and 85.5 μg 100 g^{-1}, of Capsaicin and vitamin C, respectively (Sayed *et al*. 2024).

Biofertilization of bell pepper with *Rhizophagus irregularis* and *Azotobacter chroococcum*, alone or combined with 70% chemical fertilization (50N-25P-12K) resulted in higher vitamin C (149.0 and 153.5 mg 100 g PF^{-1}) and capsaicin (5.44 and 6.11 mg g PF^{-1}) when these microorganisms were inoculated separately compared to the control, which had 128.5 mg 100 g PF^{-1} and 3.55 mg g PF^{-1}, respectively. The combination of *Rhizophagus irregularis* + *Azotobacter chroococcum* + 75% was more effective in obtaining higher concentrations of vitamin C and capsaicin, with values of 160.5 mg 100 g PF^{-1} and 6.31 mg g PF^{-1} (Sharma *et al*. 2022).

The PGPR and AMF can increase total phenol concentrations when inoculated into plants, and these can be regulators of stress caused by pathogens or abiotic stress conditions (Singh *et al*. 2014, Ureche *et al*. 2021). Singh *et al*. (2014) reported increases in phenolic acids when *Pseudomonas fluorescens* was incorporated into chickpea leaves, especially in phenolic substances such as Shikimic acid, gallic acid, tannic acid, and salicylic acid. *Mesorhizobium*, in addition to the above, increased ferulic acid, diadzein, and kaempferol compared to plants without microorganisms. In another study, Sánchez *et al*. (2022) reported lower concentrations of flavonoids (48.48 mg 100 g^{-1}), phenols (414.21 mg 100 g^{-1}), and vitamin C (22.83 g 100 g^{-1}) in xcat´ik chili plants (*Capsicum annuum* L.) biofertilized with *Bacillus subtilis* compared to plants without microbial fertilization (control), which had 51.76 mg 100 g^{-1}, 445.61 mg 100 g^{-1} and 27.48 g 100 g^{-1} of flavonoids, phenols, and vitamin C, respectively.

The increases in the nutraceutical properties of Capsicum fruits in response to biofertilizers made with PGPR and AMF, such as those observed in this study, offer benefits for human health, especially in the prevention and treatment of diseases; this is because pepper fruits have properties such as antioxidants, analgesics, anti-inflammatories, immune system stimulation, and can treat diseases such as cancer, type II diabetes, and obesity (Idrees *et al*. 2020, Akter *et al*. 2026, Li *et al*. 2026). For example, capsaicin is the compound responsible for fruit pungency and has antibacterial, antioxidant, anti-inflammatory, and anticancer properties (Ordaz and Fernández 2023).

CONCLUSIONS

Treatment with *Claroideoglomus claroideum*, *C. etunicatum*, *Glomus postulatum* and *Diversispora spurca* (AMF1) improved leaf area, fruit number and size, and total protein content in the fruits. The AMF consortia with *C. etunicatum*, *C. claroideum* and *G. postulatum* (AMF2) excelled in the variables of height and antioxidant capacity. The two PGPR improved the variables of growth, production, and nutraceutical properties compared to the control but were not better than the mycorrhizae.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

LITERATURE CITED

Akter S, Mahib MMR, Hoque MR, Islam MR, Kabir MG (2026) Comparative profiling of *Capsicum frutescens* and *C. annuum* reveals superior bioactivities and nutritional advantages for functional food applications. Food Science & Nutrition 14(1): e71426. https://doi.org/10.1002/fsn3.71426

Almaraz-Suárez JJ, González-Mancilla A, Ferrera-Cerrato R, Rodríguez Guzmán MDP, Taboada-Gaytán OR, Hernández-Cuevas LV, Alarcón A, Trinidad-Santos A (2021) Arbuscular mycorrhizal fungi in the rhizosphere of native plants and their effect on poblano pepper growth. Revista Fitotecnia Mexicana 44(4): 571-579. https://doi.org/10.35196/rfm.2021.4.571

Almaraz-Suárez JJ, Ferrera-Cerrato R, González-Mancilla A, González Mancillas R, Orona-Castillo I, Gutiérrez-Guzmán UN, Preciado-Rangel P (2022) Eficiencia fotoquímica y crecimiento de chile poblano inoculados con rizobacterias y hongos micorrízicos arbusculares: Ecosistemas y Recursos Agropecuarios 9(3): 1-10. https://doi.org/10.19136/era.a9n3.3126

Angulo-Castro A, Ferrera-Cerrato R, Alarcón A, Almaraz-Suárez JJ, Delgadillo-Martínez J, Jiménez-Fernández M, García-Barradas O (2018) Crecimiento y eficiencia fotoquímica del fotosistema II en plántulas de 2 variedades de *Capsicum annuum* L. inoculadas con rizobacterias u hongos micorrícicos arbusculares. Revista Argentina de Microbiología 50(2): 178-188. https://doi.org/10.1016/j.ram.2017.03.011

Brand-Williams W, Cuvelier ME, Berset CLWT (1995) Use of a free radical method to evaluate antioxidant activity. LWT-Food science and Technology 28(1): 25-30. https://doi.org/10.1016/S0023-6438(95)80008-5

Camacho-Rodríguez M, Almaraz-Suárez JJ, Vázquez-Vázquez C, Angulo-Castro A, Ríos-Vega M E, González-Mancilla A (2022) Effect of plant growth-promoting rhizobacteria on the growth and yield of jalapeño pepper. Revista Mexicana de Ciencias Agrícolas 13(28): 185-196. https://doi.org/10.29312/remexca.v13i28.3273

Cisneros-Pineda O, Torres-Tapia LW, Gutiérrez-Pacheco LC, Contreras-Martín F, González-Estrada T, Peraza-Sánchez SR (2007) Capsaicinoids quantification in chili peppers cultivated in the state of Yucatan, Mexico. Food Chemistry 104(4): 1755-1760. https://doi.org/10.1016/j.foodchem.2006.10.076

Doner LW, Hicks KB (1981) High-performance liquid chromatographic separation of ascorbic acid, erythorbic acid, dehydroascorbic acid, dehydroerythorbic acid, diketogulonic acid, and diketogluconic acid. Analytical Biochemistry 115(1): 225-230. https://doi.org/10.1016/0003-2697(81)90550-9

Faliarizao NT, Siddiq M, Dolan KD (2025) Total phenolics, antioxidant, and physical properties of red chili peppers (*Capsicum annuum* L.) as affected by drying methods. International Journal of Food Properties 28(1): 2492823. https://doi.org/10.1080/10942912.2025.2492823

FAOSTAT (2026) Crops and Livestock Products. Food and Agriculture Organization of the United Nations: https://www.fao.org/faostat/es/#data/QCL. Consultation date: July 26, 2026.

Gerdemann JW, Nicolson TH (1963) Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting: Transactions of the British Mycological Society 46: 235-244. https://doi.org/10.1016/S00071536(63)80079-0.

González MA, Almaraz SJJ, Ferrera CR, Rodríguez GMP, Taboada GOR, Trinidad SA, Alarcón A, Arteaga GRI (2017) Caracterización y selección de rizobacterias promotoras de crecimiento en plántulas de chile poblano (*Capsicum annuum* L.). Revista Internacional de Contaminación Ambiental 33(3): 463-474. https://doi.org/10.20937/RICA.2017.33.03.09

González-Mancilla A, Almaraz-Suárez JJ, Ferrera-Cerrato R, del Pilar Rodríguez-Guzmán M, Taboada-Gaytán OR (2024) Photosynthetic activity and growth of poblano pepper biofertilized with plant growth promoting rhizobacteria and arbuscular mycorrhizal fungi. Current Research in Microbial Sciences (7): 100269. https://doi.org/10.1016/j.crmicr.2024.100269

Hernández HJ, Tamez GP, Gómez FR, Delgado GMCE, García MMS, Robles HL, Infante RR (2021) Prevalence of *Xanthomonas euvesicatoria* (formally *X. perforans*) associated with bacterial spot severity in *Capsicum annuum* crops in South Central Chihuahua, Mexico. PeerJ 9(1): e10913. https://doi.org/10.7717/peerj.10913

Idrees I, Hanif MA, Ayub MA, Hanif A, Ansari TM (2020). Chili Pepper. In: Hanif M, Nawaz H, Khan M, Byrne H (eds) Medicinal plants of South Asia novel sources for drug discovery, 1st ed. Elsevier: Amsterdam, The Netherlands. pp. 113-124. https://doi.org/10.1016/B978-0-08-102659-5.00009-4

Kumar OA, Tata SS (2009) Ascorbic acid contents in chili peppers (*Capsicum* L.). Notulae Scientia Biologicae 1(1): 50-52. https://doi.org/10.15835/nsb113445

Li J, Qian Y, Shen M, Chen Y, Yu Q, Xie J (2026) Identification, characterization, and molecular docking of immunomodulatory peptides from *Capsicum annuum* var. conoides seed protein hydrolysates. Food Chemistry 149935. https://doi.org/10.1016/j.foodchem.2026.149935

Ordaz PL, Fernández JY (2023) Propiedades farmacológicas del chile (Capsicum) y sus beneficios en la salud humana: Una revisión bibliográfica. LATAM: Revista Latinoamericana de Ciencias Sociales y Humanidades 4(2): 267. https://doi.org/10.56712/latam.v4i2.873

Pérez ACE, Carrillo RJC, Chávez SJL, Perales SC, Enríquez del VR, Villegas AY (2017) Diagnóstico de síntomas y patógenos asociados con marchitez del chile en Valles Centrales de Oaxaca. Revista Mexicana de Ciencias Agrícolas 8(2): 281-293. https://doi.org/10.29312/remexca.v8i2.50

Ravishankar GA, Suresh B, Giridhar P, Rao SR, Johnson TS (2003) Biotechnological studies on Capsicum metabolite production and plant improvement. In: De AK (ed) Capsicum: The genus Capsicum. CRC Press. London. pp. 96-128.

Salas-Pérez L, Gaucín-Delgado JM, Preciado-Rangel P, Fortis-Hernández M, Valenzuela-García JR, Ayala-Garay AV (2016) Efecto del ácido benzoico en la capacidad antioxidante de germinados de trigo. Revista Mexicana de Ciencias Agrícolas 17: 3397-3404.

Sánchez M, Ruíz-Sánchez E, Muñoz-Rodríguez D, Chan Cupul, W, Medina-Dzul K (2022) Efecto de inoculantes microbianos en los compuestos bioactivos y actividad antioxidante del chile xcat´ ik (*Capsicum annuum* L.). Biotecnia 24(3): 123-131. https://doi.org/10.18633/biotecnia.v24i3.1691

Sánchez-Toledano BI, Cuevas-Reyes V, Kallas Z, Zegbe JA (2021) Preferences in 'jalapeño' pepper attributes: a choice study in Mexico. Foods 10(12): 1-12. https://doi.org/10.3390/foods10123111

SAS (2002) Software: the SAS System for Windows version 9.0. Statistical Analysis System. SAS Institute Inc, Cary, NC, USA.

Sayed EG, Desoukey SF, Desouky AF, Farag MF, EL-kholy RI, Azoz SN (2024) Synergistic Influence of Arbuscular mycorrhizal Fungi Inoculation with Nanoparticle Foliar Application Enhances Chili (*Capsicum annuum* L.) Antioxidant Enzymes, Anatomical Characteristics, and Productivity under Cold-Stress Conditions. Plants 13: 517. https://doi.org/10.3390/plants13040517

Sharma M, Sharma V, Delta AK, Kaushik P (2022) Rhizophagus irregularis and Nitrogen Fixing Azotobacter with a Reduced Rate of Chemical Fertilizer Application Enhances Pepper Growth along with Fruits Biochemical and Mineral Composition. Sustainability 14(9): 5653. https://doi.org/10.3390/su14095653.

SIAP-SIACON (2024) Servicio de Información Agroalimentaria y Pesquera. Sistema de Información Agroalimentaria De Consulta. Agrícola Estatal 2003-2023, México. https://www.gob.mx/siap/documentos/siacon-ng-161430. Consultation date: February 20, 2024.

Sieverding E (1983) Manual de Métodos para la Investigación de la Micorriza Vesículo-Arbuscular en el Laboratorio. Centro Internacional de Agricultura Tropical. Cali, Colombia. 121p.

Sini HN, Barzegar R, Mashaee SS, Ghahsare MG, Mousavi-Fard S, Mozafarian M (2024) Effects of biofertilizer on the production of bell pepper (*Capsicum annuum* L.) in greenhouse. Journal of Agriculture and Food Research 16: 101060. https://doi.org/10.1016/j.jafr.2024.101060.

Singh A, Jain A, Sarma BK, Upadhyay RS, Singh HB (2014) Rhizosphere competent microbial consortium mediates rapid changes in phenolic profiles in chickpea during *Sclerotium rolfsii* infection. Microbiological research 169(5-6): 353-360. https://doi.org/10.1016/j.micres.2013.09.014.

Singleton VL (1999) Analysis of total phenols and other oxidation substrates and their antioxidants by means of Folin-Ciocalteu reagent. Methods in Enzymology 299: 152-178.

Smith PK, Krohn RI, Hermanson GT, Mallia AK, Gartner FH, Provenzano MD, Fujimoto EK, Goeke NM, Olson BJ, Klenk DC (1985) Measurement of protein using bicinchoninic acid. Analytical Biochemistry 150: 76-85. https://doi.org/10.1016/0003-2697(85)90442-7

Tahmasebi A, Mirzaalian Dastjerdi A, Jamali B (2023) Microbial-based biological treatments improved the nutritional, nutraceutical and functional properties of greenhouse sweet pepper (*Capsicum annuum* L.). Frontiers Sustainable Food Systems 7: 1145972. https://doi.org/10.3389/fsufs.2023.1145972.

Ureche MAL, Pérez-Rodriguez MM, Ortiz R, Monasterio RP, Cohen AC (2021) Rhizobacteria improve the germination and modify the phenolic compound profile of pepper. *Capsicum annuum*. Rhizosphere 18: 100334. https://doi.org/10.1016/j.rhisph.2021.100334.

Zhou P, Xing D, Tu D, Peng S, He J (2026) A comparative study on the nutrient and organic acid profiles of selected pepper genotypes. Scientific Reports 16(1): 6435. https://doi.org/10.1038/s41598-026-37078-w