PGPR and vermicompost consortia improve the phytochemical quality of C*apsicum annuum* jalapeño peppers

Consorcios de PGPR y vermicompost, mejoran la calidad fitoquímica de chiles jalapeños *Capsicum annuum*

Alfonso Andrade-Sifuentes[1], Gabriel de Jesús Peña-Uribe[1], Jorge Saenz-Mata[1], Jesús Josafath Quezada-Rivera[1], Rubén Palacio-Rodríguez[1], María del Rosario Jacobo-Salcedo[2]

[1]Facultad de Ciencias Biológicas-Universidad Juárez del Estado de Durango. Av. Universidad s/n, Fracc. Filadelfia. CP. 35010. Gómez Palacio, Durango, México.
[2]Centro Nacional de Investigación Disciplinaria en Relaciones Agua Suelo Planta Atmósfera del Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias. Km. 6.5, Margen Derecha Canal Sacramento, CP. 35140. Gómez Palacio, Durango, México.

*Corresponding author: jsaenz_mata@ujed.mx

Scientific article

Received: February 26, 2026
Accepted: July 07, 2026

ABSTRACT. Jalapeño (*Capsicum annuum* L.), a crop of great economic and nutritional importance in Mexico, faces soil degradation and reduced fruit quality as a consequence of agricultural intensification. In response, the use of vermicompost and plant growth-promoting rhizobacteria (PGPR) has emerged as a sustainable biotechnological alternative to restore soil fertility and improve crop productivity. This study evaluated the effects of PGPR co-inoculation and phosphorus-enriched vermicompost on the yield and phytochemical quality of *Capsicum annuum* L. fruits, considering their influence on growth parameters and the accumulation of bioactive metabolites under a randomized complete block design with a factorial arrangement. Eight treatments were established by combining bacterial consortium (BC) inoculation and vermicompost rates (0, 20, and 40 t ha^{-1}), including a chemically fertilized control. Fruit weight, polar and equatorial diameter, firmness, yield and phytochemical properties (capsaicin, phenols, flavonoids and antioxidant capacity) were evaluated. The combined application of vermicompost and PGPR increased yield through synergistic effect, with treatment-dependent variations in phytochemical quality. Furthermore, biofertilization with PGPR at 20 t ha^{-1} produced results statistically comparable to those obtained with chemical fertilization. These findings indicate that agricultural efficiency depends on the interaction between fertilization inputs rather than on their individual application, supporting this strategy as a promising alternative for the transition toward sustainable organic nutrient management systems.
Keywords: Nutraceutical quality, antioxidants, biofertilizers, soil health, food safety.

RESUMEN. El jalapeño (*Capsicum annuum* L.), es un cultivo de gran importancia económica y nutricional en México, enfrenta degradación del suelo y reducción de la calidad del fruto como consecuencia de la intensificación agrícola. En respuesta, el uso de vermicompost y rizobacterias promotoras del crecimiento vegetal (PGPR) ha surgido como una alternativa biotecnológica sostenible para restaurar la fertilidad del suelo y mejorar la productividad del cultivo. Este estudio evaluó los efectos de la coinoculación de PGPR y vermicompost enriquecido con fósforo en el rendimiento y la calidad fitoquímica de los frutos de *Capsicum annuum* L., considerando su influencia en los parámetros de crecimiento y la acumulación de metabolitos bioactivos bajo un diseño de bloques completos aleatorizados con un arreglo factorial. Se establecieron ocho tratamientos combinando la inoculación de consorcio bacteriano (BC) y dosis de vermicompost (0, 20 y 40 t ha^{-1}), incluyendo un control fertilizado químicamente. Se evaluaron el peso del fruto, el diámetro polar y ecuatorial, la firmeza, el rendimiento y las propiedades fitoquímicas (capsaicina, fenoles, flavonoides y capacidad antioxidante). La aplicación combinada de vermicompost y PGPR aumentó el rendimiento mediante un efecto sinérgico, con variaciones en la calidad fitoquímica dependientes del tratamiento. Además, la biofertilización con PGPR a 20 t ha^{-1} produjo resultados estadísticamente comparables a los obtenidos con la fertilización química. Estos hallazgos indican que la eficiencia agrícola depende de la interacción entre los insumos de fertilización más que de su aplicación individual, lo que respalda esta estrategia como una alternativa prometedora para la transición hacia sistemas de manejo de nutrientes orgánicos sostenibles.
Palabras clave: Calidad nutracéutica, antioxidantes, biofertilizantes, salud del suelo, seguridad alimentaria.

How to cite: Andrade-Sifuentes A, Peña-Uribe G de J, Saenz-Mata J, Quezada-Rivera JJ, Palacio-Rodríguez R, Jacobo-Salcedo M del R (2026) PGPR and vermicompost consortia improve the phytochemical quality of C*apsicum annuum* jalapeño peppers. Ecosistemas y Recursos Agropecuarios Núm. Esp. VI: e5138. DOI: 10.19136/era.a13nVI.5138.

Ecosist. Recur. Agropec. Núm. Esp. VI: e5138, 2026
https://doi.org/10.19136/era.a13nVI.5138

INTRODUCTION

Jalapeño pepper (*Capsicum annuum* L.) is one of the most economically and socially important horticultural crops in Mexico due to its high domestic demand and increasing value in international markets. Furthermore, this crop is recognized for its high content of bioactive compounds, such as capsaicinoids, phenolic compounds, and carotenoids, whose concentrations determine its phytochemical quality and nutraceutical properties (Farhoudi *et al.* 2019). However, agricultural intensification and the increasing reliance on mineral fertilizers have placed considerable pressure on soil fertility, causing significant disruption to soil biological processes and ecosystem functions, thereby compromising agricultural productivity (Ali *et al.* 2024). These changes may also indirectly affect the accumulation of secondary metabolites and, consequently, fruit quality (Tziourrou *et al.* 2025). In this context, biofertilization strategies and sustainable soil management practices have emerged as viable alternatives for improving crop productivity and nutraceutical quality (Pei *et al.* 2025).

Co-inoculation with beneficial microorganisms, particularly phosphorus-solubilizing plant growth-promoting rhizobacteria (PGPR), has been shown to increase nutrient availability, stimulate the synthesis of secondary metabolites, and enhance tolerance to biotic and abiotic stresses (Fasusi *et al.* 2021, Tziourrou *et al.* 2025). Likewise, the application of vermicompost as an organic fertilizer improves soil structure and biological activity while serving as a slow-release source of nutrients, resulting in commercially viable chili pepper production (Valenzuela-García *et al.* 2019). When enriched with phosphorus, vermicompost exhibits greater agronomic potential due to the increased availability of this essential nutrient for metabolic processes involved in the biosynthesis of phytochemical compounds (Andrade-Sifuentes *et al.* 2024).

The interaction among plants, phosphorus-enriched organic fertilizers, and PGPR inoculation is a dynamic process that plays a fundamental role in plant nutrition and the sustainable management of agricultural soils (He *et al.* 2025). Consequently, this integrated strategy represents a promising approach for simultaneously improving crop yield and the nutraceutical quality of horticultural crops. Nevertheless, evidence regarding the combined effects of phosphorus-enriched organic fertilizers and PGPR co-inoculation on jalapeño pepper growth and fruit phytochemical quality remains limited. Therefore, this study aimed to evaluate the effects of PGPR co-inoculation and phosphorus-enriched vermicompost on the yield and phytochemical quality of *Capsicum annuum* L. fruits, with particular emphasis on their influence on plant growth parameters and the accumulation of bioactive metabolites.

MATERIALS AND METHODS

Establishment and experimental conditions

The study was conducted in the municipality of Lerdo, Durango, Mexico (Figure 1), in the ejido Sapioriz. This site has a very arid semi-warm climate, with annual precipitation ranging from 200 to 400 mm, occurring mainly during the summer season (BWhw climate according to the Köppen classification modified for Mexico by García, 2004). The annual mean temperature ranges from 14 to 22 °C, with June typically being the warmest month and an average maximum temperature of 30.4 °C (CONABIO 1998). The experimental field was located at 25°27′22″ LN, 103°43′15″ LW, at an altitude of 1,169 m above sea level. Jalapeño pepper plants were grown under open-field conditions during the 2023 spring-summer growing season.

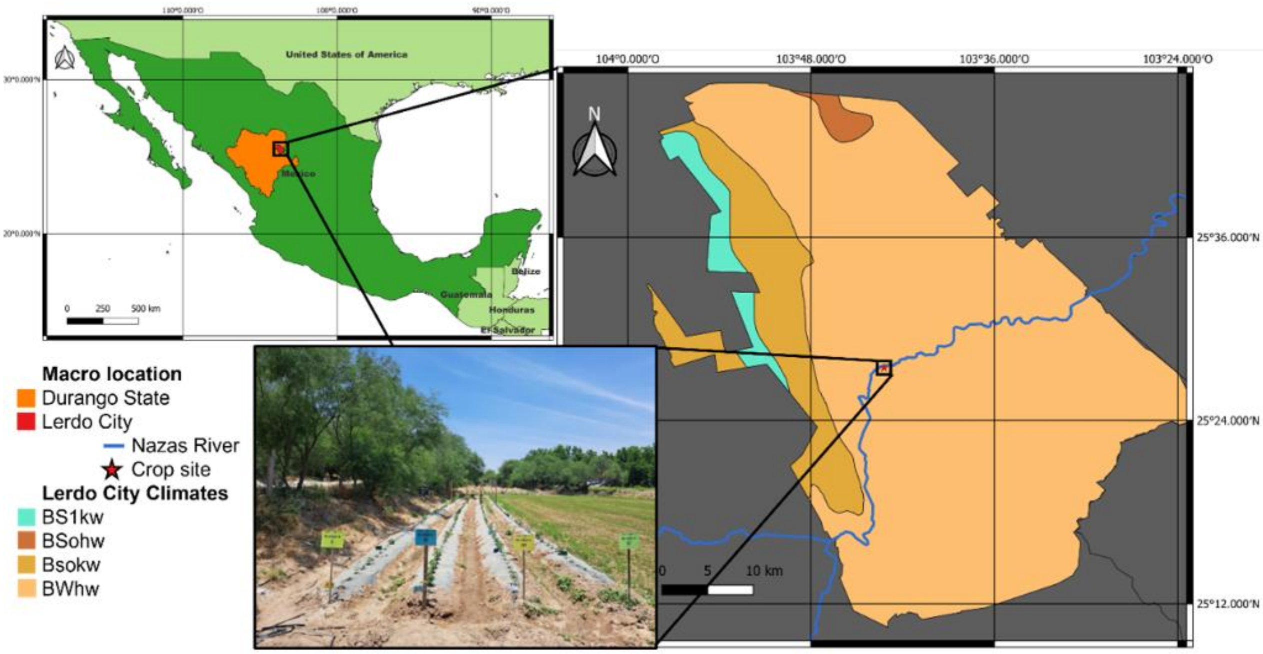

Figure 1. Location of the experimental field in the agricultural area of the Sapioriz ejido, Lerdo, Durango, Mexico.

Plant material and bacterial inoculum

The experiment was conducted using the jalapeño pepper cultivar Mixteco. Seeds were germinated in four 200-cell polystyrene trays filled with peat moss (Premier®, Mexico). Two trays were inoculated with a bacterial consortium composed of *Bacillus aryabhattai* (Crizos1) and *Bacillus subtilis* (CR7), previously characterized as plant growth-promoting rhizobacteria (PGPR) through functional assays performed at the Microbial Ecology Laboratory, Faculty of Biological Sciences, Juárez University of the State of Durango.

Bacterial strains were reactivated in Luria-Bertani (LB) broth and incubated at 37 °C with agitation at 120 rpm for 24 h. Cell concentration was adjusted to 1×10^8 CFU mL^{-1} using counts obtained with a Neubauer chamber, ensuring uniform bacterial inoculums for all inoculated treatments (Table 1).

Application of phosphorus-enriched vermicompost

The phosphorus-enriched vermicompost used in this study was obtained during the first stage of a postdoctoral research project (SECIHTI) (Andrade *et al.* 2024). Prior to field application, the vermicompost was subjected to solarization. A pile measuring 5 m in length, 1 m in width, and 0.80 m in height was prepared and adjusted to 55% moisture, monitored using a Spectrum TDR-150 moisture meter. Potable water (pH 7.0; electrical conductivity 2.6 dS m^{-1}) was used to maintain the desired moisture content.

Table 1. Treatments established using PGPR bacterial consortia, vermicompost application rates, and chemical fertilization in jalapeño pepper cultivated under open-field conditions.

Treatments	Factor 1 Vermicompost (V) (t ha^{-1})	Factor 2 Cell density of bacterial consortia CFU mL^{-1}
T1	0	1 x 10^{8}
T2	0	0
T3	20	1 x 10^{8}
T4	20	0
T5	40	1 x 10^{8}
T6	40	0
T7	Chem	1 x 10^{8}
T8	Chem	0

The pile was covered with 30-μm transparent high-albedo polyethylene plastic for 40 days, reaching temperatures of 65 ± 5 °C (Vázquez-Vázquez *et al.* 2011). After solarization, the vermicompost was incorporated into each experimental unit at rates of 0, 20, and 40 t ha^{-1} and thoroughly mixed into the upper 30 cm of soil using a shovel.

Chemical fertilization

The chemical fertilization treatment consisted of applying 160-80-0 kg ha^{-1} (N-P_2O_5-K_2O). Urea [$CO(NH_2)_2$; 46% N], monoammonium phosphate (MAP; 11% N, 52% P_2O_5), and an NK fertilizer (12% N, 46% K_2O) were used as nutrient sources. Nitrogen was applied in three equal splits: five days before transplanting, at flowering, and during fruit development. Each application was placed beside the seedlings. Phosphorus, supplied as MAP, was applied five days before transplanting. For each 4-m^2 experimental unit, fertilizer rates corresponded to 139.13 g of urea and 61.54 g of MAP.

Treatments and experimental design

Treatments were established by combining bacterial consortium (BC) inoculation with vermicompost application. Eight treatments were evaluated (Table 1), consisting of combinations of bacterial inoculation, vermicompost rates (0, 20, and 40 t ha^{-1}), and a chemically fertilized control.

The experiment was arranged in a randomized complete block design with a factorial arrangement consisting of eight treatments and four replicates, resulting in 32 experimental units under open-field conditions. Each experimental unit measured 2 × 2 m and was equipped with a drip irrigation system with emitters spaced at 0.20-m intervals. Forty-five-day-old inoculated and uninoculated jalapeño pepper seedlings (cv. Mixteco) were transplanted into the corresponding experimental units.

Variables evaluated and statistical analysis

Physical Fruit Variables

To evaluate the effects of the treatments on fruit physical quality, fruit size was determined by measuring the polar diameter (PD) and equatorial diameter (ED) using a digital Vernier caliper (Steren®, Mexico). Fruit firmness (Fms) was measured using a penetrometer equipped with a 3-

mm plunger (FHT200, Extech Instruments®, USA). Average fruit weight was determined using an analytical balance (Ohaus Model 3729®, Mexico).

Fruit yield (t ha^{-1}) was calculated from the total weight of all commercially marketable fruits harvested from each experimental unit using an ADAM analytical balance (450-g capacity). Harvests were performed on eight occasions between 50 and 89 days after transplanting (DAT), and yield was expressed in kilograms per experimental unit before conversion to tons per hectare.

Preparation of extracts

To determine the nutraceutical quality of the fruits (total phenolic compounds, total flavonoids, antioxidant capacity, and capsaicin content), fresh jalapeño pepper samples were processed immediately after harvest. Five grams of fresh fruit tissue were placed in a sterile mortar and ground under liquid nitrogen until a fine powder was obtained. From the homogenized material, 2 g of tissue collected from fruits harvested at 70 DAT were transferred to screw-cap tubes containing 10 mL of 80% ethanol and shaken at 70 rpm for 24 h (Remi RS-24BL, Jayanti Scientific). The samples were centrifuged at 3,000 rpm for 5 min, and the supernatants were collected for subsequent phytochemical analyses. All extractions were performed in triplicate for each treatment.

Capsaicin determination

Capsaicin content was determined using the colorimetric method described by Ryu *et al.* (2017). Five milliliters of *n*-hexane were added to each extract, and the mixture was allowed to stand at room temperature for 10 min to dissolve the capsaicinoids. Subsequently, 4 mL of the *n*-hexane phase were carefully transferred to a clean tube to avoid contamination.

The *n*-hexane extract was mixed with 10 mL of 0.05 N NaOH and vigorously shaken. After phase separation, the organic phase was discarded, and 1 mL of the remaining alkaline solution was mixed with 50 µL of 1 N HCl, 50 µL of 0.1% DCQ reagent, and 50 µL of 2.5% ammonia solution. The reaction mixture was incubated at room temperature for 10 min, and absorbance was measured at 600 nm.

Total phenolic compounds

The total phenolic content was determined using the Folin-Ciocalteu method (Garcia-Nava *et al.* 2009). The reaction mixture consisted of 300 µL of extract, 1,080 µL of distilled water, and 120 µL of Folin-Ciocalteu reagent (Sigma-Aldrich, St. Louis, MO, USA). After 30 min, 900 µL of 7.5% Na_2CO_3 solution were added. The mixture was incubated for an additional 30 min and allowed to stand for 10 min before absorbance was measured at 765 nm using a UV-Vis spectrophotometer (VE-5100UV). The results were expressed as mg gallic acid equivalents (GAE) per 100g fresh weight (FW).

Total flavonoids

Total flavonoid content was determined according to Lamaison and Carnet (1990). The reaction mixture consisted of 250 µL of sample, 75 µL of 5% $NaNO_2$, and 1,250 µL of distilled water. Subsequently, 150 µL of 10% $AlCl_3$, 150 µL of 1 M NaOH, and 250 µL of distilled water were added. Absorbance was measured at 510 nm using a UV-Vis spectrophotometer (VE-5100UV). Results were expressed as mg quercetin equivalents (QE) per 100g of FW.

Ecosist. Recur. Agropec. Núm. Esp. VI: e5138, 2026
https://doi.org/10.19136/era.a13nVI.5138

Antioxidant capacity

Antioxidant capacity was determined using the DPPH radical scavenging assay (Brand-Williams *et al.* 1995). An ethanolic solution containing 0.025 mg mL^{-1} DPPH• (Sigma-Aldrich) was mixed with 50 µL of extract and incubated in the dark for 25 min. Absorbance was measured at 517 nm. Results were expressed as µmol Trolox equivalents (TE) per 100 g FW.

Statistical analysis

All statistical analyses were performed using Statistica version 9.2 (StatSoft Inc., Tulsa, OK, USA). Data were first evaluated for normality using the Shapiro-Wilk test and homogeneity of variances using Levene's test before factorial analysis of variance (α = 0.05) and as *post hoc* test Tukey was used.

RESULTS

The physical characteristics of jalapeño pepper fruits were generally improved by the treatment combining 20 t ha^{-1} of vermicompost with bacterial consortium (BC) inoculation (Table 2). The second-best performance was observed in the chemically fertilized (CHF) treatment combined with bacterial consortium inoculation. As expected, the untreated control exhibited the lowest values for most of the evaluated variables, except for fresh fruit weight (FW). Factorial analysis indicated that chemical fertilization and the application of 20 t ha^{-1} of vermicompost produced the highest values for most physical traits, with no significant differences between these two fertilization treatments.

Regarding bacterial consortium inoculation, significant effects were observed for fresh fruit weight (FW), polar diameter (PD), and fruit firmness (Fms). In addition, significant interactions between fertilization treatment (chemical fertilization or 20 t ha^{-1} vermicompost) and bacterial consortium inoculation were detected for several agronomically important variables, including fresh fruit weight, number of fruits per plant (NF), yield per plant (Ypp), and yield per hectare (Yld) (Table 2; Figure 2a, b, and d).

Table 2. Morphometric variables of jalapeño chili resulting from the effect of the treatments Bacterial Consortium (BC), Vermicompost (V), and interaction (BC x V) on the FW, fresh fruit weight; PD, polar diameter; ED, equatorial diameter; NF, Number of fruits per plant; Ypp, Yield per plant; Yld, Yield and Firmness Fms.

Factor	FW	PD	ED	NF	Ypp	Yld	Fms
	g	cm	cm		g	t ha^{-1}	N
			Vermicompost				
0 (t ha^{-1})	10.20 ± 1.64^{a}	4.81 ± 0.83^{a}	2.0 ± 0.18^{a}	27 ± 6.41^{ab}	280 ± 67.6^{ab}	11.20 ± 2.70^{ab}	11.31 ± 0.55^{b}
20 (t ha^{-1})	9.38 ± 1.60^{ab}	5.03 ± 0.85^{a}	2.4 ± 2.40^{a}	34 ± 3.54^{a}	324 ± 78.8^{a}	12.95 ± 3.15^{a}	12.27 ± 1.38^{ab}
40 (t ha^{-1})	7.93 ± 0.77^{b}	4.48 ± 0.52^{a}	2.2 ± 2.21^{a}	24 ± 2.64^{b}	192 ± 28.9^{b}	7.67 ± 1.15^{b}	12.21 ± 1.00^{ab}
CHF (kg ha^{-1})	11.09 ± 0.88^{a}	5.43 ± 0.49^{a}	2.1 ± 2.08^{a}	29 ± 5.64^{ab}	318 ± 59.0^{a}	12.72 ± 2.36^{a}	13.09 ± 0.76^{a}
			Inoculation				
BC (1×10^{8}CFU mL^{-1})	10.52 ± 1.45^{a}	5.46 ± 0.51^{a}	2.25 ± 0.30^{a}	28.75 ± 5.31^{a}	306 ± 69.3^{a}	12.24 ± 3.21^{a}	12.97 ± 0.81^{a}
Without BC	8.78 ± 1.49^{b}	4.41 ± 0.52^{b}	2.11 ± 0.17^{a}	28.67 ± 6.47^{a}	250 ± 80.4^{a}	10.03 ± 2.70^{a}	11.47 ± 0.84^{b}
			Interaction Vermicompost / Inoculation				
	*	ns	ns	*	*	*	ns

± Standard deviation; the means with the same letters in a column for each factor are not statistically different (Tukey, p ≤ 0.05); CHF: chemical fertilization; * and ns = significant and non-significant according to Tukey test (p ≤ 0.05).

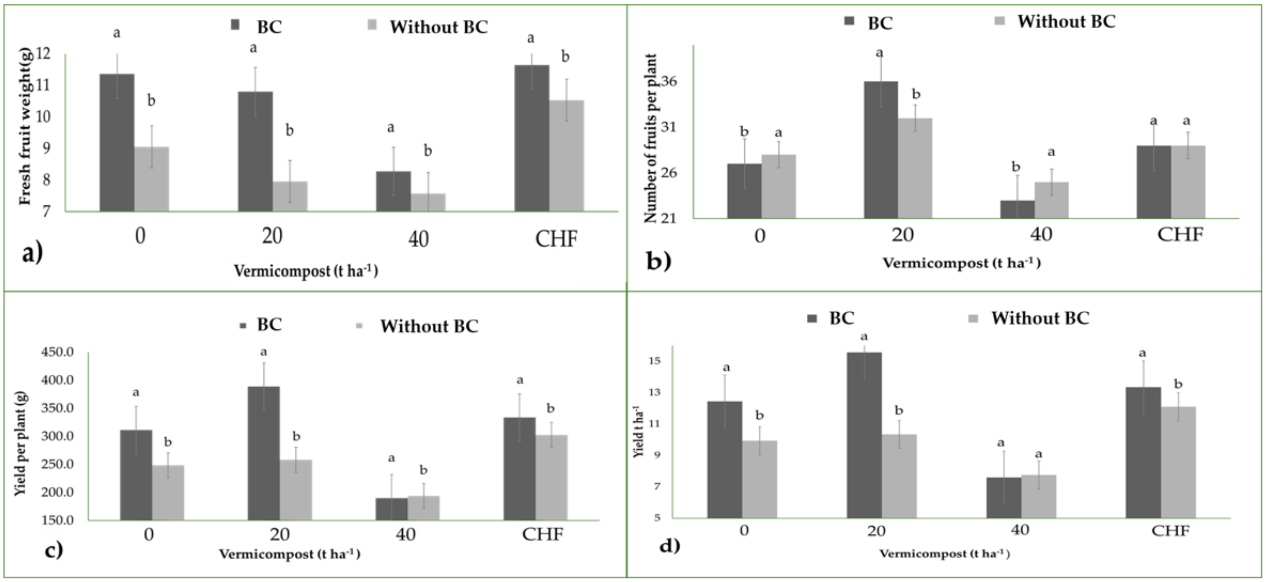

Figure 2. Interaction between bacterial consortium (BC) inoculation and vermicompost application rate on (a) fresh fruit weight (FW), (b) number of fruits per plant (NF), (c) yield per plant (Ypp), and (d) yield per hectare (Yld) of jalapeño pepper (*Capsicum annuum* L.). Vermicompost rates were 0, 20, and 40 t ha^{-1}, and CHF represents the chemical fertilization treatment. Different letters indicate significant differences among treatments according to Tukey's post hoc test ($P \leq 0.05$).

The highest yield per hectare (Table 2; Figure 2d) was obtained with treatment T3 (20 t ha^{-1} vermicompost + bacterial consortium at 1×10^8 CFU mL^{-1}), whereas the lowest yields were recorded for T5 (40 t ha^{-1} vermicompost + bacterial consortium) and T6 (40 t ha^{-1} vermicompost without bacterial inoculation). In general, treatments inoculated with the bacterial consortium produced higher yields than their corresponding non-inoculated treatments receiving the same vermicompost rate. A significant interaction between vermicompost application and bacterial consortium inoculation was observed for yield-related variables (Table 2; Figure 2).

Compared with the agronomic variables, phytochemical traits exhibited greater variability among treatments (Table 3). Capsaicin content was highest in T3 (20 t ha^{-1} vermicompost + bacterial consortium) and in the chemically fertilized treatment (CHF). In contrast, treatments receiving 40 t ha^{-1} vermicompost and the untreated control showed comparable capsaicin concentrations. For total phenolic compounds, the highest values were observed in T5 (40 t ha^{-1} vermicompost + bacterial consortium) and T8 (CHF). However, these treatments were not significantly different from T1, T2, T3, or T7 according to Tukey's multiple comparison test. The highest flavonoid contents were recorded in T5, T8, and T1. Regarding antioxidant capacity, only T1 and T2 differed significantly from the remaining treatments, exhibiting the lowest DPPH radical scavenging activity.

Factorial analysis indicated that fertilization treatment did not significantly affect capsaicin, total phenolic compounds, or flavonoid content (Table 3). In contrast, fertilization type significantly influenced antioxidant capacity (DPPH). Bacterial consortium inoculation significantly affected the evaluated phytochemical variables, and a significant interaction between fertilization treatment and bacterial consortium inoculation was detected for total phenolic compounds (Table 3; Figure 3).

Table 3. Effect of Bacterial Consortium (BC), Vermicompost (V), and interaction (BC x V) on the variables of antioxidant compounds (phytochemical quality) in *Capsicum annum* fruits.

Treatment	Capsaicin ug g^{-1}	Phenols mg 100g^{-1} (FW)	Flavonoids mg 100g^{-1} (FW)	DPPH mg 100g^{-1} (FW) Trolox eq
		Vermicompost		
0 (t ha^{-1})	2.456 ± 1.50^a	6.190 ± 1.25^a	4.587 ± 0.87^a	5.880 ± 0.20^b
20 (t ha^{-1})	3.077 ± 1.94^a	5.102 ± 1.70^a	3.943 ± 0.90^a	10.070 ± 0.22^a
40 (t ha^{-1})	2.497 ± 1.06^a	6.610 ± 2.30^a	4.541 ± 1.06^a	9.845 ± 0.24^a
CHF (Kg ha^{-1})	2.381 ± 1.93^a	7.044 ± 1.54^a	4.908 ± 0.77^a	10.214 ± 0.47^a
		Inoculation		
BC (1×10^{8}CFU mL^{-1})	2.090 ± 2.09^a	7.060 ± 1.33^a	4.868 ± 4.86^a	9.008 ± 1.79^a
Without BC	3.110 ± 1.21^a	5.416 ± 1.85^b	4.122 ± 0.98^b	9.001 ± 2.02^a
		Interaction Vermicompost / Inoculation		
	ns	*	ns	ns

± Standard deviation; the means with the same letters in a column for each factor are not statistically different ($p \leq 0.05$); CHF: chemical fertilization; * and ns = significant and non-significant according to *post hoc* Tukey test ($p \leq 0.05$).

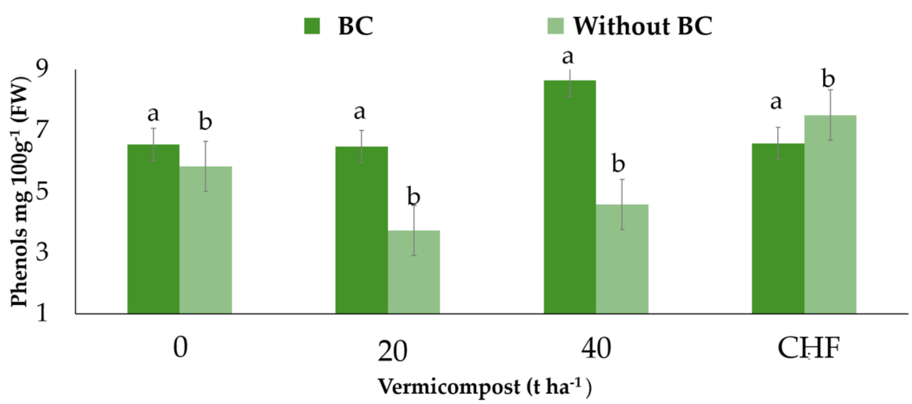

Figure 3. Interaction between bacterial consortium (BC) inoculation and vermicompost application rate on total phenolic content in jalapeño pepper fruits. Vermicompost rates were 0, 20, and 40 t ha^{-1}, and CHF represents the chemical fertilization treatment. Different letters indicate significant differences according to Tukey's post hoc test ($P \leq 0.05$).

DISCUSSION

The factorial ANOVA revealed a significant interaction between phosphorus-enriched vermicompost application and bacterial consortium inoculation (V × BC) for several agronomically important variables, including fresh fruit weight (FW), number of fruits per plant (NF), yield per plant (Ypp), and total yield (Yld) (Table 2; Figure 2). A similar interaction was observed for total phenolic compounds (Table 3; Figure 3). These findings indicate that the effect of vermicompost on crop productivity depended on the presence of PGPR, with the combined treatment consisting of 20 t ha^{-1} vermicompost and bacterial consortium inoculation producing the highest yields. Collectively, these results suggest that the combined application of vermicompost and PGPR was more effective than either practice applied individually. The main effects of vermicompost also revealed that the intermediate application rate (20 t ha^{-1}) produced higher values for several agronomic traits than the highest rate (40 t ha^{-1}). This non-linear response may be associated with excessive nutrient availability or altered soil physicochemical conditions at the higher vermicompost dose. Likewise, bacterial consortium inoculation significantly increased fresh fruit weight and fruit firmness, supporting the role of PGPR in promoting plant growth and fruit quality.

In contrast, no significant interaction was detected for fruit morphological traits, including polar diameter (PD), equatorial diameter (ED), and firmness (Fms) (Table 2). These findings suggest that these variables responded independently to vermicompost application and bacterial consortium inoculation, indicating predominantly additive rather than interactive effects.

Previous studies in tomato, jalapeño pepper, and other horticultural crops have consistently shown that vermicompost improves plant growth, including root development, stem elongation, leaf area, and fruit weight (Wang *et al*. 2017, Espinosa-Palomeque *et al*. 2020, Kalika-Singh *et al*. 2022). Differences between those studies and the present work may be explained by variation in soil nutrient availability, environmental conditions, crop management practices, or vermicompost application rates, all of which may influence both the main effects of fertilization and the magnitude of treatment interactions.

Similarly, Nawrin *et al*. (2020) reported greater polar fruit diameter and improved nutrient concentration in chili peppers following the combined application of vermicompost and boron. These findings suggest that integrating organic and inorganic nutrient sources may enhance fruit development and crop productivity. Likewise, Tlelo-Cuautle *et al*. (2020) reported that combining organic and chemical fertilization can increase crop yield while reducing environmental impacts.

Regarding phytochemical quality, a significant V × BC interaction was observed only for total phenolic compounds (Table 3; Figure 3). This finding suggests that the combined application of vermicompost and PGPR promoted the accumulation of phenolic compounds. Previous studies have shown that PGPR improve nutrient availability, particularly phosphorus and micronutrients, while inducing systemic resistance responses that may favor the biosynthesis of secondary metabolites (Alonso-Villegas *et al*. 2023). Likewise, Espinosa *et al*. (2025) proposed that improved nutrient availability together with microbial signaling may enhance phenylpropanoid metabolism.

Among the bacterial strains used in this study, *Bacillus aryabhattai* has been reported to stimulate early metabolic and physiological responses in plants (Mun *et al*. 2024), whereas *Bacillus subtilis* is widely recognized as an effective PGPR because of its biofertilizing, biostimulant, and biocontrol properties (Hashem *et al*. 2019). Furthermore, Kalika-Singh *et al.* (2022) suggested that the gradual release of nutrients from vermicompost improves nutrient availability throughout crop development, thereby supporting sustained plant growth.

No significant interaction was detected for antioxidant capacity (DPPH) or total flavonoid content. These results suggest that these traits were primarily influenced by fertilization rather than by bacterial consortium inoculation. Indeed, vermicompost treatments (20 and 40 t ha^{-1}) and chemical fertilization exhibited greater antioxidant capacity than the untreated control, indicating that nutrient availability, particularly phosphorus, may contribute to the regulation of antioxidant metabolism (Zou *et al*. 2023).

Capsaicin content did not differ significantly among treatments or experimental factors (Table 3), suggesting that this trait remained relatively stable under the conditions evaluated. Although the combined treatment (20 t ha^{-1} vermicompost plus bacterial consortium inoculation) exhibited the highest numerical value, this trend was not statistically significant and should therefore be interpreted cautiously. Previous studies have suggested that phosphorus availability and PGPR inoculation may enhance ATP production and metabolic pathways associated with capsaicin biosynthesis (Datta *et al*. 2015). However, because these physiological processes were not directly evaluated in the present study, such mechanisms remain speculative.

CONCLUSIONS

The present study demonstrated that the combined application of phosphorus-enriched vermicompost and plant growth-promoting rhizobacteria (PGPR) significantly improved yield-related variables, including fruit weight, number of fruits per plant, yield per plant, and total yield. Among the evaluated treatments, the intermediate vermicompost rate (20 t ha^{-1}) combined with bacterial consortium inoculation produced the highest agronomic performance, whereas the highest vermicompost rate (40 t ha^{-1}) resulted in reduced yield, indicating a non-linear response to vermicompost application. In contrast, fruit morphological traits, including polar diameter, equatorial diameter, and firmness, responded independently to the evaluated factors and showed no significant interaction between vermicompost application and PGPR inoculation. Regarding phytochemical quality, total phenolic compounds exhibited a significant interaction between both factors, whereas antioxidant capacity and flavonoid content were influenced primarily by fertilization treatment. Overall, these findings indicate that the combined use of phosphorus-enriched vermicompost and PGPR represents a promising biofertilization strategy for improving the productivity of *Capsicum annuum* L. while modulating selected phytochemical traits associated with fruit quality. The results further highlight the importance of considering the interaction between organic amendments and beneficial microorganisms when designing sustainable nutrient management strategies.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI) for the financial support provided for this study. We also thank Mr. J. Reyes Servando Gutiérrez Castaño, an *ejidatario* from the Sapioriz community, Durango, Mexico, for generously providing the agricultural field where the experiment was conducted and for his valuable collaboration throughout the study. We also acknowledge the technical staff of the CENID RASPA laboratory for their assistance with the laboratory analyses.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ADDITIONAL INFORMATION

This research was supported in part by the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI), with a postdoctoral fellowship number of CVU 560948.

STATEMENT ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

Artificial intelligence (AI)-based language tools were used solely to assist with the review of grammar, punctuation, and syntax. The authors carefully reviewed and verified all revisions and assume full responsibility for the content, scientific accuracy, and final version of the manuscript.

LITERATURE CITED

Ali A, Liu X, Yang W, Li W, Chen J, Qiao Y, Gao Z, Yang Z (2024) Impact of bio-organic fertilizer incorporation on soil nutrients, enzymatic activity, and microbial community in wheat–maize rotation system. Agronomy 14(9): Article 1942. https://doi.org/10.3390/agronomy14091942

Alonso-Villegas R, González-Amaro RM, Figueroa-Hernández CY, Rodríguez-Buenfil IM (2023) The genus Capsicum: A review of bioactive properties of its polyphenolic and capsaicinoid composition. Molecules 28(10): Article 4239. https://doi.org/10.3390/molecules28104239

Andrade-Sifuentes A, Peña-Uribe G de J, Sáenz-Mata J, Quezada-Rivera JJ, Palacio-Rodríguez R, Muro-Pérez G (2024) The integration of phosphorus-solubilizing rhizobacteria, *Eisenia fetida* and phosphorus rock improves the availability of assimilable phosphorus in the vermicompost. Sustainability 16(17): Article 7576. https://doi.org/10.3390/su16177576

Brand-Williams W, Cuvelier ME, Berset C (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

Datta M, Paul D, Sinha SN, Sengupta C (2015) Plant growth promoting rhizobacteria improve the production and enhancement of alkaloid content in chilli. Frontiers in Environmental Microbiology 1(2): 24-26. https://doi: 10.11648/j.fem.20150102.13

Espinosa DFG, Pérez-Álvarez S, Sánchez-Chávez E, Uranga-Valencia LP, Ochoa-Chaparro EH, Escobedo-Bonilla CM, Contreras-Martínez R, Leyva-Hernández HA (2025) Sustainable biostimulation in chili cultivation: Effects of PGPMs and marine algal extracts on the physiological performance of serrano pepper crop. Sustainability 17(17): Article 8090. https://doi.org/10.3390/su17178090

Espinosa-Palomeque B, Cano-Ríos P, Salas-Pérez L, González-Rodríguez G, Reyes-González A, Ayala-Garay VA, Preciado-Rangel P (2020) Vermicompost on the production and nutraceutical quality of jalapeño pepper fruits (*Capsicum annuum* L.). Terra Latinoamericana 38(4): 795-803. https://doi.org/10.28940/terra.v38i4.722

Farhoudi R, Mehrnia MA, Lee DJ (2019) Antioxidant activities and bioactive compounds of five jalapeño peppers (*Capsicum annuum*) cultivars. Natural Product Research 33(6): 871-874. https://doi.org/10.1080/14786419.2017.1410801

Fasusi OA, Cruz C, Babalola OO (2021) Agricultural sustainability: Microbial biofertilizers in rhizosphere management. Agriculture 11(2): Article 163. https://doi.org/10.3390/agriculture11020163

García E (2004) Modificaciones al sistema de clasificación climática de Köppen. 5ª ed. Instituto de Geografía, Universidad Nacional Autónoma de México. Serie Libro Num. 6. México. 90p.

García-Nava MA (2009) Cuantificación de fenoles y flavonoides totales en extractos naturales. Revista Académica 1: 1-4.

Hashem A, Tabassum B, Abd-Allah EF (2019) *Bacillus subtilis*: A plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi Journal of Biological Sciences 26(6): 1291-1297. https://doi.org/10.1016/j.sjbs.2019.05.004

He Y, Ning Z, Cui Y, Yue X, Huang Y, Zhu C (2025) Combination of functional complementary salt-tolerant PGPR and organic amendments modulates the soil micro-environment and promotes wheat growth. Agriculture 15(24): Article 2558. https://doi.org/10.3390/agriculture15242558

Kalika-Singh S, Ansari A, Maharaj G (2022) Vegetable crop cultivation using vermicompost in comparison to chemical fertilizers: A review. Agricultural Reviews 43(4): 480-484. https://doi.org/10.18805/ag.RF-234

Lamaison JLC, Carnet A (1990) Teneurs en principaux flavonoïdes des fleurs de *Crataegus monogyna* Jacq. et de *Crataegus laevigata* (Poiret D. C.) en fonction de la végétation. Pharmaceutica Acta Helvetiae 65: 315-320.

Mun BG, Hussain A, Park YG, Kang SM, Lee IJ, Yun BW (2024) The PGPR *Bacillus aryabhattai* promotes soybean growth via nutrient and chlorophyll maintenance and the production of butanoic acid. Frontiers in Plant Science 15: Article 1341993. https://doi.org/10.3389/fpls.2024.1341993

Nawrin KS, Uddin MJ, Ali AHMZ, Rahman MK (2020) Effects of boron and vermicompost on growth, yield and nutrient content of chilli (*Capsicum annuum* L.). Journal of Biodiversity Conservation and Bioresource Management 6(1): 31-36. https://doi.org/10.3329/jbcbm.v6i1.51329.

Pei B, Liu T, Xue Z, Cao J, Zhang Y, Yu M, Liu E, Xing J, Wang F, Ren X, Zhang Z (2025) Effects of biofertilizer on yield and quality of crops and properties of soil under field conditions in China: A meta-analysis. Agriculture 15(10): Article 1066. https://doi.org/10.3390/agriculture15101066

Ryu WK, Kim HW, Kim GD, Rhee HI (2017) Rapid determination of capsaicinoids by colorimetric method. Journal of Food and Drug Analysis 25(4): 798-803. https://doi.org/10.1016/j.jfda.2016.11.007

Tlelo-Cuautle AM, Taboada-Gaytán OR, Cruz-Hernández J, López-Sánchez H, López PA (2020) Efecto de la fertilización orgánica y química en el rendimiento de fruto de chile poblano. Revista Fitotecnia Mexicana 43(3): 283-289. https://doi.org/10.35196/rfm.2020.3.238

Tziourrou P, Golia EE (2025) Phytoremediation of co-contaminated environments: A review of microplastic and heavy metal/organic pollutant interactions and plant-based removal approaches. Soil Systems 9(4): Article 137. https://doi.org/10.3390/soilsystems9040137

Valenzuela-García AA, Figueroa-Viramontes U, Salazar-Sosa E, Orona-Castillo I, Gallegos-Robles MÁ, García-Hernández JL, Troyo-Diéguez E (2019) Effect of organic and inorganic fertilizers on the yield and quality of jalapeño pepper fruit (*Capsicum annuum* L.). Agriculture 9(10): Article 208. https://doi.org/10.3390/agriculture9100208

Vázquez-Vázquez C, García-Hernández JL, Salazar-Sosa E, López-Martínez JD, Valdez-Cepeda RD, Orona-Castillo I, Gallegos-Robles MÁ, Preciado-Rangel P (2011) Aplicación de estiércol solarizado al suelo y la producción de chile jalapeño (*Capsicum annuum* L.). Revista Chapingo Serie Horticultura 17: 69-74.

Wang XX, Zhao F, Zhang G, Zhang Y, Yang L (2017) Vermicompost improves tomato yield and quality and the biochemical properties of soils with different tomato planting history in a greenhouse study. Frontiers in Plant Science 8: Article 1978. https://doi.org/10.3389/fpls.2017.01978

Zou Y, Liu J, Ding Y, Wang X, Zhang Y (2023) Phosphorus supply regulates capsaicinoid biosynthesis and fruit quality in pepper (*Capsicum annuum* L.) through modulation of carbon–nitrogen metabolism. Scientia Horticulturae 314: Article 111345. https://doi.org/10.1016/j.scienta.2023.111345