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RESEARCH ARTICLE

Mineral concentration in fruit of two ecotypes of goldenberry with low chemical fertilization and rhizobacteria

Isaac Guajardo-Paz[1], Rosalinda Mendoza-Villarreal[1*], Manuel Sandoval-Villa[2], Valentín Robledo-Torres[1], José Rafael Paredes-Jácome[1], and Álvaro Morelos-Moreno[1]

[1]Universidad Autónoma Agraria Antonio Narro, Departamento de Horticultura, 25315, Saltillo, Coahuila, México.
[2]Colegio de Postgraduados Campus Montecillo, 56230, Texcoco, Estado de México, México.
[*]Corresponding author (rosalinda.mendoza@uaaan.edu.mx)
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ABSTRACT

It is a great challenge to achieve sustainable agriculture, due to the current problems of over-fertilization and the contamination that this generates, therefore, it is necessary to use ecological methods such as rhizobacteria and different plant materials. Goldenberry (*Physalis peruviana* L.) appears in the market of exotic fruits, which are highly nutritious, besides adapting to diverse conditions; however, in Mexico it has been little studied. The objective of the present work was to evaluate the mineral concentration of goldenberry fruits with a low chemical fertilization (CF) regime in two ecotypes Sacha and Chiclayo, applying rhizobacteria, which were planted in a greenhouse with passive ventilation, drip irrigation and clay soil, under a randomized block design with factorial arrangement. In each ecotype, a consortium of rhizobacteria (PC-UA) and a commercial product of *Pseudomonas fluorescens* (PF) was applied at a dose of 1×10^8 colony forming units mL^{-1}, in combination with CF at 25% and 50% concentration, and two controls only with CF at 25% and 50%. The PF with 50% CF increased P concentration by 49%, K by 56%, S by 54%, and Fe by 42% in Sacha; PF together with 25% CF increased Mg by 55% in Sacha; PC-UA with 25% CF increased P concentration by 46%, S by 51%, and Fe by 40% in Chiclayo, all of the above compared to the control with Sacha. Under the conditions of the experiment, the combination of PC-UA with Chiclayo, and PF with Sacha promotes goldenberry fruits with high mineral concentration and sustainable crop.

Key words: Goldenberry, low fertilization, minerals, rhizobacteria, sustainability.

INTRODUCTION

Currently, sustainable agriculture, along with food security, is a necessity, but at the same time a great challenge, since reaching this goal implies overcoming difficulties of a social, economic or environmental nature (FAO, FIDA, OMS, PMA, UNICEF, 2024). Among these difficulties are inadequate crop management practices linked to intensive use of agrochemicals, including fertilizers, because this has contributed to pollution and ecological crisis; biogeochemical cycles have been altered, and the soil has been degraded, gaining salts, but losing biodiversity and fertility (Hoque et al., 2022). In this sense, cultivated plants are exposed to greater biotic and abiotic stress, and their production decreases (Monroy-Velandia and Coy-Barrera, 2021). Plant growth-promoting rhizobacteria (PGPR) are one of the most affordable options for agricultural production not to depend only on agrochemicals, thus, managing reduction of such effects of pollution, and successively achieve a productive and sustainable agriculture at the same time (Woo and Pepe, 2018).

Their capacity to improve production is due to fact that they act in symbiosis with plants through different mechanisms: Among the PGPR, the genus *Pseudomonas* stands out, as it is characterized by

producing the auxin indole-acetic acid, creating siderophores, and solubilizing phosphates (Rawat et al., 2020), and this makes it possible to reduce the use of chemical fertilizers (Schenk et al., 2024). When PGPR are applied in association, their effectiveness increases, as the flow of nutrients is more efficient, and in part the natural rhizospheric microbiome is restored (Woo and Pepe, 2018).

For its part, the *Physalis peruviana* L. plant is known thanks to its fruit: Goldenberry, cape gooseberry or uchuva and is part of the market of exotic fruits of Andean origin, like other berries, it has worldwide importance, because it has medicinal biomolecules, high nutrient content, bioactive compounds and antioxidants that positively affect human health; besides standing out in its concentration in minerals (Añibarro-Ortega et al., 2025).

Goldenberry is native of the Andes in South America, and has the ability to adapt to diverse conditions, due to its characteristics and high genetic diversity (Garzón-Martínez et al., 2015); there are numerous ecotypes worldwide; however, information on these in Mexico is still scarce. In the available studies with different plant materials is found the research of Orozco-Balbuena et al. (2021), where they evaluate the phenology of four ecotypes of goldenberry in hydroponics. Taking into consideration the above, the objective of this research was to evaluate the mineral concentration of goldenberry fruits with a low chemical fertilization regime in two ecotypes, applying rhizobacteria, based on the hypothesis that the use of these will increase the mineral concentration of the fruits in at least one of the ecotypes analyzed, while achieving a sustainable crop.

MATERIALS AND METHODS

Material and location

Goldenberry (*Physalis peruviana* L.) seeds of the Chiclayo (from Peru) and Sacha (from Ecuador) ecotypes were sown in 200-cavity polystyrene trays, with Sphagnum peat (Premier Tech Horticulture, Rivière-du-Loup, Quebec, Canada) and mineral perlite (Hortiperl from Termolita, Ciudad Santa Catarina, Nuevo León, Mexico) as substrate, in a 70:30 ratio (v/v).

Sixty days after sowing, the goldenberry plants were transplanted in a tunnel type greenhouse with passive ventilation, in clay soil mulched with black plastic and drip irrigation system, at the Universidad Autónoma Agraria Antonio Narro (UAAAN), in Saltillo (25°23'36" N, 101°00'02" W, 1785 m a.s.l.), Coahuila, Mexico.

Treatment characteristics

To plants of each ecotype was applied a plant growth promoting rhizobacteria (PGPR) consortium based on *Pseudomonas* sp., *Enterobacter* sp. and *Achromobacter* sp. (PC-UA) and a commercial product (Bio-Organik Pseudomonas, Bio-Organik, Tangancícuaro, Michoacán, Mexico) of *Pseudomonas fluorescens* (PF) at a dose of 1×10^8 colony forming units (CFU) mL^{-1}, their combination with chemical fertilization (CF) at 25% and 50%, and two controls only with CF at each concentration (T), so that 12 treatments with three replicates were obtained (Table 1).

Previously, the rhizobacteria in the consortium were isolated from the rhizosphere of tomato (*Solanum lycopersicum* L.) crop grown in open fields in calcareous soils of General Cepeda, Coahuila, Mexico. They were molecularly identified based on 16S rRNA (Chávez-Arteaga et al., 2018) at the Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Unidad Irapuato; and using the "botón en césped" method based on the work of Bauer et al. (1966) it was determined that these were not antagonistic. The strains were cultured until a concentration of 1×10^8 CFU mL^{-1} was obtained. During the crop cycle the rhizobacteria were applied three times in liquid form to the base of the stem, 20 mL per plant, with the concentration mentioned above.

Table 1. Treatments applied to the greenhouse goldenberry crop in Saltillo, Mexico. PGPR: Plant growth promoting rhizobacteria; *P. fluorescens*: *Pseudomonas fluorescens*.

Treatment	Ecotype	Chemical fertilization concentration (%)	Rhizobacteria	Acronym
1	Sacha	25	Without PGPR	T:25:Sa
2	Sacha	50	Without PGPR	T:50:Sa
3	Sacha	25	PGPR consortium	PC-UA:25:Sa
4	Sacha	50	PGPR consortium	PC-UA:50:Sa
5	Sacha	25	*P. fluorescens* commercial product	PF:25:Sa
6	Sacha	50	*P. fluorescens* commercial product	PF:50:Sa
7	Chiclayo	25	Without PGPR	T:25:Ch
8	Chiclayo	50	Without PGPR	T:50:Ch
9	Chiclayo	25	PGPR consortium	PC-UA:25:Ch
10	Chiclayo	50	PGPR consortium	PC-UA:50:Ch
11	Chiclayo	25	*P. fluorescens* commercial product	PF:25:Ch
12	Chiclayo	50	*P. fluorescens* commercial product	PF:50:Ch

Crop management

Before starting cultivation, the land was leveled and decompacted (subsoiling) with a precision motor cultivator (Pasquali XB40, Abbiategrasso, Milan, Italy). The soil was analyzed, and sampling was based on the collection of subsamples, extracting small quantities (20 cm deep) in a zigzag pattern at nine different points throughout the area, avoiding the edges. The subsamples were mixed homogeneously to form a composite sample, from which 1 kg was extracted. This was dried for a period of 6 d, taken to a sieve with a diameter of 2 mm, and then bagged, labeled, and sent to the Soil and Nutrition Analysis Laboratory of the company Fertilidad de Suelos S. de R.L., Celaya, Guanajuato, Mexico. The soil analysis results were used to calculate the approximate volume needed to lixiviate out salts with irrigation, reducing the electrical conductivity (EC) to approximately 5 dS m^{-1}. A volume of 100 L d^{-1} was applied to the soil in each row for 45 d, calculated using the following formula:

$$\mathrm{NI} = \frac{\mathrm{EC1} - \mathrm{EC2}}{\mathrm{EC1}}$$

where NI is need for irrigation, EC1 is initial electrical conductivity (EC), EC2 is desired EC (Duarte-González, 2020). Substituting the data obtained from the soil analysis:

$$\mathrm{NI} = \frac{13.4 - 5}{13.4} = 0.627$$

Therefore, 62.7% of a volume of water equivalent to the total volume of soil was needed to lower the initial EC to 5 dS m^{-1}. The total volume of soil: 1 m × 21 m × 0.3 m (measurements of the row) = 6.3 m^3. Therefore, 62.7% was equivalent to 3.95 m^3 water, or 3950 L water, which was rounded up to 4000 L and applied to each row over a total of 40 d, or 100 L daily. This was continued for 5 d until the EC decreased to 5.1 dS m^{-1}. Likewise, 0.2 kg m^{-2} solarized vermicompost with a maturation time of 6 mo was added to increase organic matter, to create a favorable environment for the colonization and effectiveness of rhizobacteria acting as a soil conditioner, and also contributing to reducing EC (Song et al., 2015). The distance between rows was 1.5 m and 0.5 m between plants, double row, with a density of 26 666 plants ha^{-1}. The plant was managed at four stems, tended with raffia attached to hooks for tutorship. At 35 d after transplanting (DAT) flowering began, and 95 DAT the harvest began, making a cutting every week, for the data of this experiment the last four cuttings of the crop cycle were evaluated.

Based on the results of the water analysis (Table 2), fertilization was calculated according to the Steiner nutrient solution (content in milliequivalents at 25% and 50% respectively: 3.0 and 6.0 NO_3, 0.25 and 0.5 H_3PO_4, 1.75 and 3.5 K, 2.25 and 4.5 Ca, 1.0 and 2.0 Mg, 1.75 and 3.5 S, EC = 0.5 and 1.0 dS m^{-1}) and prepared with: Potassium nitrate (KNO_3), calcium nitrate ($Ca(NO_3)_2{\cdot}4H_2O$), monopotassium phosphate (KH_2PO_4), magnesium nitrate ($Mg(NO_3)_2$), a mixture of micronutrients (Ultrasol micro mix, Sociedad Química y Minera de Chile - SQM

Comercial de Mexico S.A. de C.V., Zapopan, Jalisco, Mexico), 85% nitric acid (HNO_3), and 90% sulfuric acid (H_2SO_4). Doses of 25% and 50% were used to activate rhizobacteria, because a dose of 100% does not allow them to perform their activity in the rhizosphere adequately and can reduce their population (Xiao et al., 2022). This nutrient solution was applied via irrigation, and was prepared in 1100 L tanks, covered to avoid sunlight. The amount of irrigation varied from 1 to 2 L^{-1} $plant^{-1}$ d^{-1}, from 0 to 95 DAT, and after 95 DAT, respectively, according to crop phenology. Temperatures ranged from 5 to 45 °C throughout the crop cycle.

Table 2. Characteristics and ion content of irrigation water used in the experiment.

Determination				Value	
pH				7.43	
Electrical conductivity (EC), dS m^{-1}				0.95	
Sodium adsorption ratio (SAR)				2.17	
Ion	mg L^{-1}	Ion	mg L^{-1}	Ion	mg L^{-1}
Nitrate	5.46	Sulfate	80.20	Chloride	42.70
Phosphate	0.00	Copper	0.007	Sodium	85.30
Potassium	5.85	Iron	0.013	Arsenic	0.001
Calcium	77.60	Boron	0.55	Bicarbonate	370.00
Magnesium	23.40	Zinc	0.056	Carbonate	0.00

Variables evaluated

A total of 90 fruits per treatment (30 per replicate) were collected at harvest maturity, and their N, P, K, Ca, Mg, S, Cu, Fe and B concentrations were determined; for which the samples were dehydrated in a forced air oven (HCF-125, Riossa, Guadalajara, Jalisco, Mexico) for 72 h at 70 °C and then were ground in a mortar.

The N concentration was determined based on the Kjeldahl method for total N, using the extract resulting from the wet digestion of the dry sample with a mixture of H_2SO_4 and perchloric acid ($HClO_4$) 2:1 (v/v) and adding 1 mL 30% hydrogen peroxide, and in an aliquot of 10 mL digest, by distillation of the sample and titration with H_2SO_4 at 0.05 normal. For the determination of the other minerals, the same procedure was carried out, only changing to a mixture of HNO_3 and $HClO_4$ 2:1 (v/v) and in an aliquot of 5 mL digest; subsequently, the extracts were read in an inductively coupled plasma/optical emission spectrometer (ICP-OES) (725-ES, Varian, Palo Alto, California, USA); in both procedures blanks were used to eliminate any possible error due to the manipulation of the samples (Alcántar and Sandoval, 1999).

Statistical analysis

A randomized block design with factorial arrangement was used, with three factors: The PGPR applied, with three levels (T, PC-UA, and PF), the fertilization dose with two levels (25%, and 50%), and the ecotype with two levels (Sacha and Chiclayo). To understand the relationship between the factors mentioned and the data obtained, a principal component analysis (PCA) was performed on the correlation matrix of the variables, with the InfoStat program version 2020 (Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina). All data passed the Anderson-Darling normality test. A factorial ANOVA was performed to evaluate the simultaneous effect of the factors and their interaction on each variable, and a one-way ANOVA was performed to analyze the effect of each factor. The Tukey mean comparison test ($p \leq 0.05$) was performed using Minitab version 19 statistical program.

RESULTS AND DISCUSSION

Soil analysis

At the end of the crop cycle, soil analysis shows a decrease in both electrical conductivity (EC) and mineral concentration. There was a 97% decrease for nitrate, 59% for K, and 84% for S, likewise, Na was reduced by 74%, being the least reduction in P, Ca, and Mg, with 29%, 11%, and 34%, respectively (Table 3). The above means that, as no base fertilization was applied to the soil, nutrient extraction by the crop occurred, having a requirement

especially for N and S (Miranda and Fischer, 2021), also due to the fact that plant growth promoting rhizobacteria (PGPR) used part of them in their metabolism, because, although their nutritional requirements are simple, they need minerals and C sources, which come both from the environment and from root exudates (Rawat et al., 2020). However, there was a reduction in soil EC and an increase in organic matter (Table 4), which is very positive from the perspective of agricultural production (Monroy-Velandia and Coy-Barrera, 2021).

Table 3. Mineral content of the soil where experiment was established at the start and at the end of the crop cycle.

Determination	Result at the start	Result at the end
	mg kg^{-1}	mg kg^{-1}
Nitrate	680	22
P-Olsen	203	144
K	762	312
Ca	3687	3272
Mg	580	380
S	1218	200
Na	1085	282

Table 4. Characteristics of the soil where experiment was established at the start and at the end of the crop cycle.

Determination	Result at the start	Result at the end
Textural class	Clay	Clay
Bulk density, g cm^{-3}	1.11	1.11
Organic matter, %	2.58	3.32
pH	8.07	7.80
Electric conductivity (EC), dS m^{-1}	13.40	3.46
Cation exchange capacity (CEC), $mol_{(+)}$ kg^{-1} soil	29.50	21.50

Relationship and interaction between rhizobacteria, fertilization, and ecotype

The PCA results showed that the treatments PGPR consortium (PC-UA), 25% chemical fertilization (CF), Chiclayo (PC-UA:25:Ch), without PGPR, 50% CF, Chiclayo (T:50:Ch), and *Pseudomonas fluorescens*, 50% CF, Sacha (PF:50:Sa) are positively related to five of the minerals (variables) analyzed, including Fe, K, P, S, and Mg, while N, Cu, and B are more associated with the PGPR consortium, 25% CF, Sacha (PC-UA:25:Sa) and No PGPR, 50% CF, Sacha (T:50:Sa) treatments, and have no correlation with the above minerals. On other hand, the treatment without PGPR, 25% CF, Sacha (T:25:Sa) is not associated with any mineral due to its negative position on the axis of both principal components, which explain 74.7% of variability of the data (Figure 1). In this multivariate analysis it is observed that only the treatments in combinations can be highlighted, and not just one specific factor.

The *p*-values and R^2 coefficient obtained in the factorial ANOVA are shown in Table 5. For the P variable, the PGPR factor and the PGPR×Ecotype interaction produced significant differences, highlighting the CF level, which was 21% higher than the control (T) level (treatment without PGPR). In K, the interaction of PGPR×Ecotype resulted in significant differences. In the case of Ca, the Chiclayo ecotype showed higher content than Sacha; however, without significant differences according to Tukey ($p \leq 0.05$). For its part, Mg showed significant differences in the PGPR factor and the interaction of PGPR×Ecotype, being higher when PF was applied, with an increase of 21.6% compared to treatment T. Similarly, in S, the PGPR factor at the PF level significantly exceeded the T level by 25.7%, and the Chiclayo ecotype showed higher content than Sacha, but without significant differences according to Tukey ($p \leq 0.05$). The Cu variable in the PGPR factor and PGPR×CF interaction showed differences, but these were nonsignificant according to Tukey ($p \leq 0.05$). In the Fe variable, the PGPR factor showed significant differences and PGPR×Ecotype interaction,

highlighting the levels with PF and PC-UA rhizobacteria, which were 19.2% and 20.3% higher than the T level, respectively. In the case of B, there were significant differences in the ecotype factor and in the PGPR×CF interaction, with Sacha standing out, which increased the values by 26.5% compared to Chiclayo (Table 6).

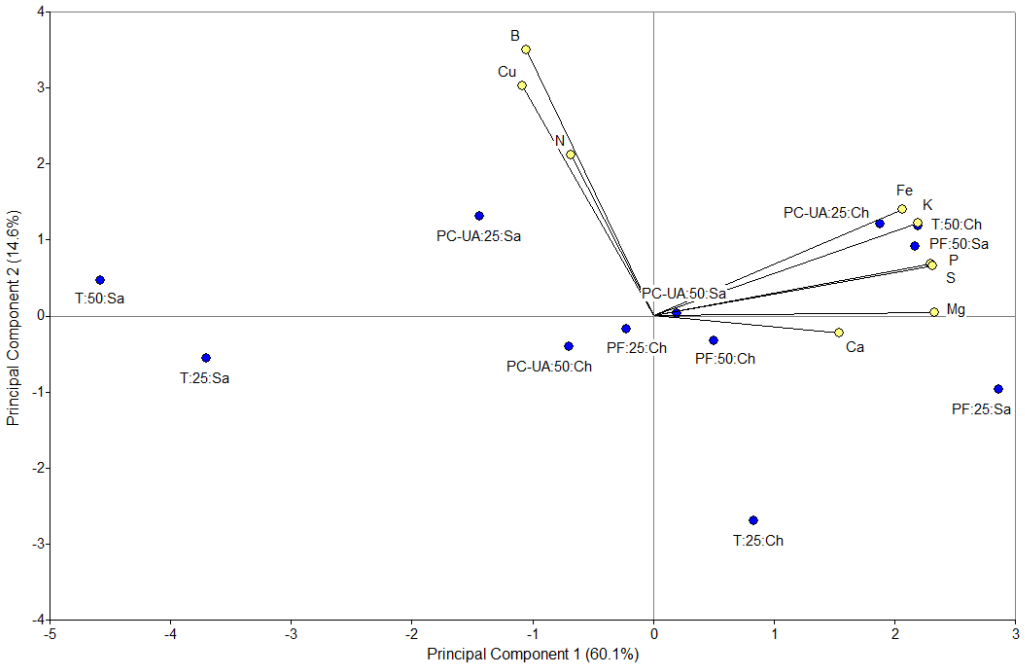

Figure 1. Principal component analysis biplot. Blue dots: observations, vectors ending in yellow dots: variables. PGPR: Plant growth promoting rhizobacteria; T: Two controls only with CF at each concentration; PC-UA: PGPR consortium based on *Pseudomonas* sp., *Enterobacter* sp. and *Achromobacter* sp.; PF: *Pseudomonas fluorescens* commercial product; 25: 25% chemical fertilization; 50: 50% chemical fertilization; Sa: Sacha ecotype; Ch: Chiclayo ecotype.

Table 5. Results obtained from factorial ANOVA for the mineral content of goldenberry fruit. *Significance $p \leq 0.05$. PGPR: Plant growth-promoting rhizobacteria; CF: low chemical fertilization.

Variable	N	P	K	Ca	Mg	S	Cu	Fe	B
Factors					*p* value				
PGPR	0.444	0.003*	0.057	0.837	0.008*	0.001*	0.047*	0.013*	0.075
CF	0.999	0.300	0.998	0.122	0.528	0.826	0.162	0.148	0.524
Ecotype	0.490	0.030*	0.201	0.050*	0.074	0.049*	0.526	0.172	0.001*
PGPR×CF	0.739	0.404	0.184	0.125	0.538	0.356	0.033*	0.935	0.007*
PGPR×Ecotype	0.350	0.000*	0.001*	0.154	0.000*	0.000*	0.113	0.015*	0.199
CF×Ecotype	0.400	0.620	0.660	0.411	0.906	0.867	0.133	0.935	0.075
PGPR×CF×Ecotype	0.060	0.064	0.152	0.184	0.071	0.134	0.518	0.243	0.515
R^2 value, %	38.90	73.52	62.93	48.78	71.18	73.09	56.89	56.74	67.36

Table 6. Effect of each level of significant factors on the mineral content of goldenberry fruit. Means with different letters within the same column are significantly different. (Tukey, $p \leq 0.05$; ^{NS}Nonsignificant). PGPR: Plant growth-promoting rhizobacteria; CF: low chemical fertilization; T: two controls only with CF at each concentration; PC-UA: consortium of rhizobacteria based on *Pseudomonas* sp., *Enterobacter* sp. and *Achromobacter* sp.; PF: *Pseudomonas fluorescens*.

Variable, mg 100 g^{-1}	P	Ca	Mg	S	Cu	Fe	B
Factors and their levels							
PGPR (T)	1077.0^{b}	^{NS}	578.4^{b}	917.9^{b}	6.73^{a}	26.06^{b}	^{NS}
PGPR (PC-UA)	1254.9^{ab}	^{NS}	642.1^{ab}	1074.4^{ab}	7.57^{a}	32.71^{a}	^{NS}
PGPR (PF)	1363.3^{a}	^{NS}	737.6^{a}	1235.7^{a}	5.71^{a}	32.27^{a}	^{NS}
CF (25%)	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}
CF (50%)	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}	^{NS}
Ecotype (Sacha)	1161.5^{a}	297.1^{a}	^{NS}	1012.8^{a}	^{NS}	^{NS}	18.90^{a}
Ecotype (Chiclayo)	1302.0^{a}	366.6^{a}	^{NS}	1139.2^{a}	^{NS}	^{NS}	13.90^{b}

Mineral concentration in the fruit

For N concentration, results were obtained with nonsignificant difference (Table 7), similar to those obtained in the factorial ANOVA, with averages between 1.5% and 2%; as for the work of Rueda et al. (2016) they report values of 2.4% to 2.8% N in foliar analysis when *Azospirillum* spp. and *Azotobacter* spp. were applied under different levels of N fertilization. The highest concentration of N in plants is found in the foliar part and in growth sites, even though it is an essential component in biological molecules; however, it is an important fact since it is also found as amino acids in seeds (Pilbeam, 2015), which are numerous in goldenberry fruit (Balaguera-López et al., 2020). It may seem that the rhizobacteria applied did not significantly influence the N concentration in the fruit; however, taking into account that there were no differences between treatments, this confirms their influence on N uptake in the situation where the CF is 25%, and that it can be noticed to a greater extent, in the plant's uptake of N from the soil (Bernados et al., 2024).

For P concentration, values ranging from 78.5 to 155 mg 100 g^{-1} were obtained on average, showing significant differences (Table 7). These values are higher than those reported for goldenberry fruit: 49 to 53 mg 100 g^{-1} (Obregón-La Rosa et al., 2023). The treatments PF:50:Sa, PC-UA:25:Ch, T:50:Ch, and PF:25:Sa increased P concentration between 42.5% and 49.3% with respect to the treatments T:25:Sa and T:50:Sa, that is, the Sacha ecotype together with PF promoted an increase in P in fruit, while the opposite happened without PGPR, and the interesting case of T:50:Ch also had high values without PGPR and 50% of CF (Table 7). These results are consistent with those obtained in the factorial ANOVA and confirm that the PGPR used can solubilize soil P through metabolites such as organic acids and protons, but that their effectiveness will depend on the environment, the amount of CF provided and the particular plant (Rawat et al., 2020); it is possible that high temperatures recorded have also favored the mobilization and absorption of this mineral, since the biochemical reactions of the soil, roots and microorganisms are accelerated, and therefore, there is greater production of the aforementioned metabolites (Hopkins, 2015). Furthermore, it was initially present in high quantities in the soil (Table 3), which may also have influenced the results.

Likewise, for K concentration in fruit there were significant differences. The PF:50:Sa treatment produced 56% higher K concentration than the T:25:Sa and T:50:Sa treatments, and T:50:Ch increased it by 55% compared to T:50:Sa. Thus, the values fluctuated between 387 and 898 mg 100 g^{-1} (Table 7), exceeding the range of 205 to 314 mg 100 g^{-1} reported by Zereahannes et al. (2025). In the factorial ANOVA, it was observed that the interaction of the PGPR×Ecotype factor produced significant differences, and it can be noticed that in the same T:50 treatment there is a different response, only changing ecotype, being the higher value in Chiclayo; the reason must be in its speed of adaptation to the conditions of this specific experiment, therefore, different expression of the genotype (Garzón-Martínez et al., 2015), without the need for symbiosis with PF, compared to Sacha; something similar was found by Naumova et al. (2019), where the cultivar influenced the yield of the tomatillo crop, even when high concentrations of K are positively related to such yield.

Similar to the findings in the factorial ANOVA in the variable of Ca concentration in fruit, the values did not show significant differences, reaching averages of 22 to 45 mg 100 g^{-1} (Table 7), lower than the 52.7 mg 100 g^{-1}

found by Obregón-La Rosa et al. (2023); however, they were higher than the 13 to 20 mg 100 g^{-1} reported by Zereahannes et al. (2025). It seems that by its presence in the clay soil of this experiment, the interaction between PGPR and the plant was improved, because Ca functions as a signaling tool to establish an effective symbiosis with PGPR, and regulate functions related to stress responses (Agaras et al., 2023). Its high concentration in fruit may also be related to the decrease in the presence of cracked fruit obtained at the end of the cycle (data not shown), a problem that represents a considerable loss in the production of this species (Miranda and Fischer, 2021).

Table 7. Effect of plant growth promoting rhizobacteria (PGPR) and low chemical fertilization on the mineral content of goldenberry fruit. Means with different letters within the same column are significantly different (Tukey, $p \leq 0.05$). Values next to average correspond to standard deviation. T: Two controls only with CF at each concentration; PC-UA: consortium of rhizobacteria based on *Pseudomonas* sp., *Enterobacter* sp. and *Achromobacter* sp.; PF: *Pseudomonas fluorescens*.; 25: 25% chemical fertilization; 50: 50% chemical fertilization; Sa: Sacha ecotype; Ch: Chiclayo ecotype.

Treatment	N	P	K	Ca	Mg
	%	mg 100 g^{-1}			
T:25:Sa	2.00 ± 0.26^{a}	81.9 ± 9.4^{bc}	389.6 ± 37.8^{bc}	25.1 ± 9.2^{a}	45.7 ± 7.8^{bc}
T:50:Sa	1.77 ± 0.11^{a}	78.5 ± 15.9^{c}	386.6 ± 194.7^{c}	22.4 ± 9.1^{a}	37.0 ± 9.8^{c}
PC-UA:25:Sa	1.75 ± 0.23^{a}	109.8 ± 28.9^{abc}	556.3 ± 195.0^{abc}	32.1 ± 11.4^{a}	60.1 ± 15.2^{abc}
PC-UA:50:Sa	1.70 ± 0.44^{a}	129.1 ± 23.6^{abc}	566.0 ± 84.6^{abc}	32.4 ± 6.0^{a}	64.5 ± 13.2^{abc}
PF:25:Sa	1.70 ± 0.20^{a}	142.5 ± 24.8^{a}	830.3 ± 290.0^{abc}	44.2 ± 3.6^{a}	83.7 ± 11.6^{a}
PF:50:Sa	1.80 ± 0.13^{a}	155.0 ± 27.6^{a}	897.6 ± 261.4^{a}	22.0 ± 8.4^{a}	79.3 ± 22.2^{ab}
T:25:Ch	1.52 ± 0.08^{a}	125.1 ± 12.7^{abc}	618.1 ± 64.0^{abc}	35.3 ± 7.3^{a}	71.0 ± 10.6^{abc}
T:50:Ch	1.90 ± 0.10^{a}	145.1 ± 8.7^{a}	863.9 ± 128.9^{ab}	45.3 ± 14.9^{a}	77.7 ± 3.5^{ab}
PC-UA:25:Ch	1.70 ± 0.26^{a}	145.7 ± 17.1^{a}	826.1 ± 131.3^{abc}	40.0 ± 17.6^{a}	76.5 ± 11.6^{ab}
PC-UA:50:Ch	1.63 ± 0.21^{a}	117.3 ± 7.3^{abc}	542.5 ± 69.9^{abc}	27.8 ± 9.6^{a}	55.6 ± 6.0^{abc}
PF:25:Ch	1.90 ± 0.10^{a}	114.7 ± 8.7^{abc}	625.6 ± 137.9^{abc}	38.6 ± 3.9^{a}	61.9 ± 5.0^{abc}
PF:50:Ch	1.77 ± 0.14^{a}	133.2 ± 12.8^{ab}	588.8 ± 115.6^{abc}	33.0 ± 6.5^{a}	70.1 ± 11.5^{abc}
Treatment	S	Cu	Fe	B	
	mg 100 g^{-1}				
T:25:Sa	68.7 ± 7.8^{b}	0.65 ± 0.18^{a}	2.10 ± 0.63^{b}	1.60 ± 0.45^{abc}	
T:50:Sa	63.4 ± 16.9^{b}	0.82 ± 0.13^{a}	2.08 ± 0.64^{b}	2.42 ± 0.79^{a}	
PC-UA:25:Sa	97.1 ± 26.9^{ab}	0.89 ± 0.32^{a}	2.89 ± 0.51^{ab}	2.22 ± 0.59^{ab}	
PC-UA:50:Sa	103.8 ± 15.4^{ab}	0.57 ± 0.08^{a}	3.49 ± 1.08^{a}	1.93 ± 0.40^{abc}	
PF:25:Sa	134.5 ± 22.8^{a}	0.41 ± 0.09^{a}	3.28 ± 0.55^{a}	1.35 ± 0.43^{abc}	
PF:50:Sa	140.2 ± 33.4^{a}	0.54 ± 0.22^{a}	3.59 ± 0.61^{a}	1.82 ± 0.29^{abc}	
T:25:Ch	107.6 ± 11.1^{ab}	0.46 ± 0.07^{a}	2.74 ± 0.21^{ab}	0.89 ± 0.29^{c}	
T:50:Ch	127.5 ± 9.5^{a}	0.76 ± 0.09^{a}	3.50 ± 0.38^{a}	1.47 ± 0.15^{abc}	
PC-UA:25:Ch	129.1 ± 17.2^{a}	0.76 ± 0.24^{a}	3.45 ± 0.26^{a}	1.93 ± 0.14^{abc}	
PC-UA:50:Ch	99.8 ± 12.8^{ab}	0.80 ± 0.19^{a}	3.25 ± 0.26^{a}	1.33 ± 0.40^{abc}	
PF:25:Ch	104.6 ± 9.3^{ab}	0.57 ± 0.11^{a}	2.90 ± 0.34^{ab}	1.59 ± 0.19^{abc}	
PF:50:Ch	115.0 ± 15.6^{ab}	0.75 ± 0.17^{a}	3.13 ± 0.41^{a}	1.13 ± 0.33^{bc}	

The average results for Mg concentration ranged from 37 to 83.7 mg 100 g^{-1} (Table 7), exceeding the 23 mg 100 g^{-1} indicated in the literature (Obregón-La Rosa et al., 2023). There were significant differences, the PF:25:Sa treatment produced an increase of 45% to 55% Mg with respect to the T:25:Sa and T:50:Sa treatments; likewise, the PF:50:Sa, T:50:Ch, and PC-UA:25:Ch treatments increased it 53.3% compared to T:50:Sa (Table 7). It is possible that, because of the PGPR applied, no antagonistic interaction between K and Mg or Ca cations occurred, since these elements can be distributed in plant tissues through the same cation

channels, with homologous channels also existing in some bacteria (Yan et al., 2018), and on the contrary its absorption was favored, as it happened in the case of P, since with this it can maintain synergy, in addition, from the chemical point of view, it has a large hydration diameter that confers it the capacity to react with other compounds and little retention in the soil particles, which gives it a greater availability (Grzebisz, 2015).

The fruit showed significant differences in S concentration, with PF:50:Sa, PF:25:Sa, PC-UA:25:Ch, and T:50:Ch treatments producing 46% to 54% higher concentrations compared to T:25:Sa and T:50:Sa treatments. The values obtained were in the range of 63.4 to 140.2 mg 100 g^{-1} (Table 7), which differed from the 190 mg 100 g^{-1} found by Galelli et al. (2024) in tomato fruits, but exceeded the 23 mg 100 g^{-1} reported in goldenberry (Obregón-La Rosa et al., 2023). Perhaps PGPR, especially PF, participated in S mineralization, making sulfate available from organic sources, such as the genera *Salmonella*, *Enterobacter*, *Pseudomonas*, among others, which possess sulfatase enzymes (Paniagua-Vargas and García-Oliva, 2022). This is in line with the factorial ANOVA, and in general it can be observed that PF together with the Sacha ecotype produce higher values in Mg and S concentration.

In the concentration of Cu in fruit, there were non-significant differences in accordance with factorial ANOVA, the values fluctuated between 0.41 and 0.89 mg 100 g^{-1}, so they are similar to the concentration of 0.76 mg 100 g^{-1} in tomato fruit (Galelli et al., 2024). This may be due to the fact that Cu is not very mobile and there is normally higher concentration in plant roots (Yruela, 2015). The application of *Paenibacillus* and *Bacillus* have shown in corn that they can maintain the level of Cu absorption where it does not cause phytotoxicity (Abdel-Latef et al., 2020), promote its absorption in deficiency conditions, and maintain its content with very small changes in plant tissues when there are excess amounts of another metal, although this will depend on the species and tissue in question (Galelli et al., 2024).

In the Fe concentration variable, the PF:50 and PC-UA:50 treatments of both ecotypes, PF:25:Sa, PC-UA:25:Ch, and T:50:Ch presented values 33% to 42% higher than the T:25:Sa and T:50:Sa treatments (without PGPR), which meant significant differences (Table 7), similarly to what was observed in the factorial ANOVA, where PF and PC-UA outperform the treatment T. The resulting values are higher than the 0.5 to 1.4 mg 100 g^{-1} obtained in goldenberry (Añibarro-Ortega et al., 2025; Zereahannes et al., 2025), since in this work they were 2.08 to 3.59 mg 100 g^{-1}. It is possible that the applied PGPRs have made more Fe available, forming siderophores, chelates and by decreasing soil pH, since it is a metal that is not very mobile in alkaline or calcareous soils such as the one in this work (Barker and Stratton, 2015). Other studies have found that *Pseudomonas* strains increase nutrient extraction and the growth of blackberry plants (Cabanzo-Atilano et al., 2024), even when subjected to salt stress, as they increase the absorption capacity of the roots (Kumar et al., 2020).

For the results of B concentration, there were significant differences, since the T:50:Sa treatment produced 53% and 63% higher concentrations in relation to the PF:50:Ch and T:25:Ch treatments, respectively; for its part, the PC-UA:25:Sa treatment also increased it by 60% compared to T:25:Ch (Table 7), so the results are consistent with those obtained in the factorial ANOVA, where Sacha outperforms Chiclayo. The values obtained range from 0.89 to 2.42 mg 100 g^{-1}, which are higher than 0.6 mg 100 g^{-1} found in goldenberry (Obregón-La Rosa et al., 2023). It should be noted that T:50:Sa came out higher, because contrary to the other mineral variables where there was significant difference, it resulted to be the treatment that produced lower values, and particularly highlighting the results found in K, as this coincides with the antagonism that K presents with B, both with a marked influence on the production and quality of fruits, such as goldenberry, indicating its relevance in the translocation of carbohydrates (Fageria, 2015).

It should be noted that there were inherent limitations in this research, as there was no constant monitoring of the soil throughout the crop cycle, and due to the temperatures recorded in the environment, thermal stress could have been generated. However, thanks to the combinated application of vermicompost, encouraging results were obtained for the characteristics of the site of this experiment. It is likely that the application of these organic amendments, through osmotic adjustment, regulated the balance of phytohormones, metabolite levels, and the antioxidant system, mitigating stress and promoting greater nutrient absorption by plants (Song et al., 2015; Hoque et al., 2022; Schenk et al., 2024).

CONCLUSIONS

The consortium of *Pseudomonas* sp., *Enterobacter* sp. and *Achromobacter* sp. showed preference for the Chiclayo ecotype, and their application in combination with 25% chemical fertilization increased the concentration of P, S and Fe in goldenberry fruit. *Pseudomonas fluorescens* showed a preference for the Sacha ecotype, and its application combined with 50% chemical fertilization increased the concentration of P, K, S, and Fe, and its application combined with 25% chemical fertilization increased the concentration of Mg in the goldenberry fruit.

Under the conditions of the experiment, with the use of plant growth promoting rhizobacteria of the genus *Pseudomonas* produces goldenberry fruit with high mineral concentration, savings in fertilizer costs, and sustainable production alternatives.

Author contribution

Conceptualization: I.G-P., R.M-V. Methodology: M.S-V., R.M-V. Software: I.G-P., J.R.P-J. Validation: R.M-V., M.S-V., A.M-M., V.R-T., J.R.P-J. Formal analysis: I.G-P., R.M-V. Investigation: I.G-P., R.M-V., M.S-V. Resources: R.M-V., M.S-V. Data curation: I.G-P., J.R.P-J., A.M-M. Writing-original draft: I.G-P. Writing-review & editing: R.M-V., M.S-V., A.M-M., V.R-T., J.R.P-J., I.G-P. Visualization: I.G-P. Supervision: R.M-V., V.R-T., J.R.P-J., M.S-V., A.M-M. Project administration: R.M-V., M.S-V. Funding acquisition: R.M-V., M.S-V. All co-authors reviewed the final version and approved the manuscript before submission.

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