Antioxidant activity and bioactive compounds in peanut (*Arachis hypogeaea* L.), biofortified with potassium iodide

Actividad antioxidante y compuestos bioactivos en el cacahuate (*Arachis hypogeaea* L.), biofortificado con yoduro de potasio

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ABSTRACT. Iodine is an essential micronutrient for human health, particularly due to its critical role in thyroid metabolism. Its deficiency can lead to goiter, hypothyroidism, and neurological disorders in children. This study evaluates and compares the effects of iodine on photosynthetic pigments and bioactive compounds in the peanut plant (*Arachis hypogaea* L.). Five iodine concentrations (0.000, 0.050, 0.100, 0.150, and 0.200 mM L^{-1}) were examined across four treatments and one control through foliar spraying 90 days after transplanting. The response variables included photosynthetic pigments (chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids) and bioactive compounds (total carbohydrates, total anthocyanins, and antioxidant capacity). The results show that the 0.200 mM L^{-1} concentration produced significant effects in bioactive compounds and performance, surpassing values reported in studies. These findings indicate that iodine application can serve as an effective strategy to enhance the nutritional quality of crops and contribute to mitigating micronutrient deficiencies in human populations. Furthermore, inoculation with nitrogen-fixing bacteria supports greater agricultural productivity while reducing dependence on inorganic fertilizers. Overall, this research provides valuable insights for strengthening food security.
Keywords: Biofortification, bioactive compounds, potassium Iodide, peanut.

RESUMEN. El yodo es un micronutriente esencial para la salud humana, especialmente por su función en el metabolismo tiroideo. Su deficiencia puede provocar bocio, hipotiroidismo y alteraciones neurológicas en la infancia. En este estudio se evalúan y comparan los efectos del yodo sobre los pigmentos fotosintéticos y los compuestos bioactivos en la planta de cacahuate (*Arachis hypogeaea* L.). La investigación contempla cinco concentraciones de yodo (0.000; 0.050; 0.100; 0.150 y 0.200 mM L^{-1}), distribuidas en cuatro tratamientos y un control mediante aspersión foliar a los 90 días después del trasplante. Las variables de respuesta incluyen pigmentos fotosintéticos (clorofila a, clorofila b, clorofila total y carotenoides) y compuestos bioactivos (antocianinas totales y capacidad antioxidante), además de carbohidratos totales. Los resultados indican que la concentración de 0.200 mM L^{-1} genera efectos significativos en los compuestos bioactivos y rendimiento, superando valores reportados en estudios. Estos hallazgos sugieren que el yodo puede ser una herramienta eficaz para mejorar la calidad nutricional de los cultivos y contribuir a mitigar la deficiencia de micronutrientes en la población. Además, la inoculación con bacterias fijadoras de nitrógeno favorece el rendimiento agrícola y reduce la dependencia de fertilizantes inorgánicos. En conjunto, estos resultados ofrecen perspectivas relevantes para fortalecer la seguridad alimentaria.
Palabras clave: Biofortificación, compuestos bioactivos, yoduro de potasio, cacahuate.

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INTRODUCTION

Peanuts (*Arachis hypogaea* L.) contain high levels of fiber, proteins, fats, carbohydrates and vitamins (Montero-Torres 2020). Their inclusion in the daily diet, especially in regions of Africa and Asia, helps prevent chronic diseases thanks to their antioxidant properties and their rich content of omega-6 (linoleic acid) and omega-3 fatty acids (Gutierres *et al*. 2025). Despite the agronomic and nutritional benefits of peanut cultivation in Mexico, the planted area of this oilseed has decreased by nearly 40% over the last decade. Currently, peanut cultivation covers approximately 60 000 hectares, with yields of 2.8 t ha^{-1} irrigated and 1.3 t ha^{-1} non-irrigated (França *et al*. 2021). In general, the application of iodine in agricultural crops aims to enhance key nutritional processes by improving the availability and uptake of macro and micronutrients such as nitrogen, phosphorus, potassium, and calcium (Budke *et al*. 2021). These improvements contribute to increase plant biomass and more efficient fruit and crop development, without altering the physicochemical characteristics that confer resistance to environmental stress and ensure high-quality production (Dixit *et al*. 2018).

Peanuts contain valuable biochemical constituents, including fats, proteins, carbohydrates, crude fiber, ash, and moisture (Wang 2016). From a nutritional standpoint, the synthesis of photosynthetic pigments, anthocyanins, and proteins plays a crucial role in promoting the assimilation and fixation of nitrogen, phosphorus, and potassium in legume pod crops (Sánchez *et al*. 2018). Iodine can induce the synthesis of ascorbate, β-carotene, and cysteine-rich polypeptides, which facilitate the intestinal absorption of essential mineral elements and inhibit polyphenolic polypeptides, among other metabolites (Sánchez-Acosta *et al*. 2025). Likewise, iodine applications-particularly in the form of iodide-have been shown to enhance and improve the availability of key macronutrients required for fruit production (Li *et al*. 2017). Foliar iodine supplementation is considered an efficient strategy in plants, especially when addressing iodine deficiencies that must ultimately be compensated for in the human diet (Weng *et al*. 2014, Ortega-Ramirez *et al*. 2025).

The application of iodine through inorganic salts such as potassium iodide has been shown to enhance plant tolerance to abiotic stress (Gupta *et al*. 2015). Although iodine is not naturally present in most crops—largely because plants are unable to absorb it efficiently—and irrigation through drip systems does not ensure its availability (Leija-Martínez *et al*. 2016), its supplementation can still influence several physiological and biochemical traits. In peanuts, for example, the reddish protective skin (red shell) is often discarded, despite containing bioactive compounds such as luteolin, a flavonoid with recognized antioxidant, anti-inflammatory, and antimutagenic properties (San-Martín *et al*. 2017). However, the percentage of free radical inhibition associated with this antioxidant capacity remains insufficiently documented. The generation of knowledge in this study addresses this gap by examining the response of photosynthetic pigments and bioactive compounds to iodine supplementation. Consequently, the primary objective of this research was to evaluate the antioxidant activity, the profile of bioactive compounds and photosynthetic pigment dynamics in peanut plants biofortified with potassium iodide.

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MATERIALS AND METHODS

This research took place on the experimental field of the Tecnológico Nacional de México-Instituto Tecnológico del Valle del Guadiana, located on the Durango-Mexico Highway, at Km 22.5, in the Ejido Villa Montemorelos, Durango. Its geographical coordinates are 24.0100° LN and 104.4445° LW. The soil is predominantly clay, with an average moisture retention capacity of 0 to 7%. Rainfall occurs from June to September with an average of 490 mm (Medina *et al*. 2005). For this research, similar treatment with nitrogen-fixing bacteria were used to demonstrate changes in the physicochemical properties of the peanut crop through organic fertilization based on amino acids.

Agronomic management in experimental area

Approximately 2 kg of Virginia peanut seeds were purchased from Héroes de México, located in Rodeo, Durango. The shells were removed, leaving only the clean kernels for direct sowing. Before sowing, the seeds were inoculated with nitrogen-fixing bacteria (Biokomplet) from Agribest® (2 g) in a 19 L container. A 1:2 ratio was used, and subsequently, 50% of the surface was moistened with drip tape. The seeds were sown directly in the soil of the experimental area at a density of 24 plants per row, for a total of 120 plants in the entire plot. The distance between rows was 2 m, and between plants, 30 cm. Plant nutrition consisted of organic fertilization with NitroBac Plus from Agribest®, which was applied by spraying every 8 days in all treatments. Potassium iodide was also applied via foliar spray (Silva-Marrufo *et al*. 2020).

All applications were prepared for each pre-printed trigger sprayer (TOLCO, Mexico) (10 mL), with a volume and frequency of 0.2 mL per plant. Doses were administered according to plant assimilation, expressed in millimoles per liter (mM L^{-1}), and weighed using a Scout® Pro SP202 portable electronic scale (Ohaus, Parsippany-Troy Hills, USA). The solution was prepared with 1 L of water and mixed with 1 mL of AgriBest® dispersant in four sprayers labeled according to each treatment. Regarding the minerals, three applications were made in the morning every 15 days to promote plant stimulation, foliar absorption, and pod and grain formation. The growing cycle lasted five months, and the time from planting to analysis was 2.5 months.

Experimental design

Potassium iodide was adapted and applied at different concentrations (0.000, 0.050, 0.100, 0.150, and 0.200-mM L^{-1}) by foliar spraying and supported by fertigation using organic fertilizers enriched with minerals. The statistical design consisted of a completely randomized approach using five plants per treatment, selecting a total of 25 plants to compare photosynthetic pigments and bioactive compounds in the peanut shell and kernel. Data analysis was performed using SPSS software version 2020® for Windows, following the methodology of Rivadeneira-Pacheco *et al*. (2020). Mean comparisons were carried out using Tukey’s test at a 0.05 significance level.

Plant sampling

For each evaluated variable, potassium iodide concentrations (0.000, 0.050, 0.100, 0.150, and 0.200 mM L^{-1}) were applied by foliar spraying. Each application included five replicates, resulting in a total of 25 experimental units (each plant represented one experimental unit). Beginning two months after planting, all treatments were applied for 10 days using a spray bottle with a 1 L capacity and 1 mL of Agribest® adherent–dispersant. In the treatments (potassium iodide concentrations), photosynthetic pigments, percentage of free radical inhibition (antioxidant capacity), and bioactive compounds were subsequently compared.

Variables evaluated

Pod quality and yield

Nine plants per treatment were considered for the evaluation of pod quality and yield. Pod length was estimated using 10 pods per plant. A digital caliper (500-192-30 Mitutoyo Co.) was used, and the measurement was recorded for each sample to determine pole length. Results were expressed in centimeters (cm). The total number of grains per plant, the weight of 100 seeds per plant, and the final yield per plant were quantified using the same pods. These results were reported in grams (g) and grams per plant (g/plant^{-1}). Finally, yield per unit area was calculated considering the total plant density and the yield per plant. The final results were expressed in kilograms per hectare (kg/ha^{-1}).

Photosynthetic pigments

These measurements were performed following the methodology of Wellburn (1994), with minimal modifications. Eight days after the application of iodine by foliar spray, chlorophylls a, b, total chlorophyll and total carotenoids were determined. Sixty milligrams of fresh crushed leaf tissue were placed in a screw-top test tube, to which 10 ml of 98% methanol were added. The samples were kept at room temperature, in darkness, for 24 h. Absorbance readings were then quantified using a Genesys 30sV spectrophotometer (Thermo Scientific, Waltham, Massachusetts, USA) at wavelengths of 666, 653, and 470 nm. Finally, the corresponding equations were used to calculate pigment concentrations, expressed in milligrams per gram of fresh weight (mg g^{-1} FW), in the following formulas.

$$Chl\ a = [15.65(A_{666}) - 7.34(A_{653})]$$

$$Chl\ b = [27.05(A_{653}) - 11.21(A_{666})]$$

$$Chl\ totals = [(Chl\ a)(Chl\ b)]$$

$$Carotenoids = \frac{[1000(A_{470}) - 2.86(Chl\ a) - 129.2(Chl\ b)]}{221}$$

Quantification of total carbohydrate

For quantifying total carbohydrates, the methodology of Albalasmeh *et al.* (2013) was used with minor modifications. One gram of peanut shell and kernel sample was weighed, ground using a ceramic mortar, and mixed with 4 mL of 97 % sulfuric acid. The mixture was allowed to stand for 24 h, after which the aliquot was removed and analyzed at a wavelength of 320 nm. For equipment calibration, a cuvette containing only sulfuric acid at low temperature was used as a blank (Itagaki 1994). The samples were quantified using a Genesys 30sV spectrophotometer (Thermo Scientific, Waltham, Massachusetts, USA), and the results were reported in grams.

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Quantification of total anthocyanins

Regarding total anthocyanins as bioactive compounds, the methodology of Bursać *et al*. (2015) was followed to prepare two buffer solutions: the first with potassium chloride (KCl) adjusted to pH 1.0, and the second with sodium acetate adjusted to pH 4.5.

Subsequently, 25 µL of buffer solution 1, 0.5 mL of buffer solution 2, and 0.5 mL of the methanolic extract from each sample (peanut shell and kernel) were transferred into 10 mL test tubes with caps. To homogenize the mixtures, the tubes were placed on a digital vortex mixer (Datamed, USA) for 15 min at 100 rpm and then centrifuged for approximately 15 min at 2 500 rpm (García-Cruz *et al*. 2021). For each treatment, 100 µL aliquots were transferred to cuvettes and subjected to readings at wavelengths of 520 nm and 700 nm using a Genesys 30sV spectrophotometer (Thermo Scientific, Waltham, Massachusetts, USA) (Alavarsa-Cascales *et al*. 2022).

Anthocyanin concentrations were calculated using Formula and expressed as milligram equivalents of anthocyanins per milliliter (mg EA mL^{-1}). In this formula, A represents absorbance derived from Formula; MW is the molecular weight of cyanidin-3-glucoside (449.2 g mol^{-1}); DF is the dilution factor; and ε is the molar extinction coefficient of cyanidin-3-glucoside (26 900 L mol^{-1} cm^{-1}). The constant 0.38 corresponds to the optical path length (cm), and 10^3 is the conversion factor from grams to milligrams.

$$Anthocyanin = \frac{(A\ MW\ DF\ 103)}{(£\ 0.38)}$$

$$A = (A_{520} - A_{700})\ Ph_{1.0} - (A_{520} - A_{700})\ Ph_{4.5}$$

Antioxidant capacity under the ABTS method

The antioxidant capacity was quantified following the methodology of Enciso-Gutiérrez *et al*. (2010). A 10 mL test tube was used to place 1 g of each sample (peanut shell, reddish skin, and peanut grain), 20 mL of ethyl alcohol, and 6 mL of distilled water, obtaining a 1:3 ratio. At the end of the procedure, the mixture was covered and stored for 72 hours in the absence of light. According to the methodology of Martysiak-Zurowska and Wenta (2012), 100 µL of the hydroalcoholic extract of each sample and 1 mL of the ABTS radical solution were used. The $ABTS^+$ solution was prepared by mixing 5 mL of a 7 mM ABTS solution with 88 µL of a 140 mM potassium persulfate solution. This preparation was then diluted in an ascorbic acid buffer to reach a pH of 5.0 and an absorbance of 0.7 nm.

All measurements were taken at a wavelength of 734 nm after 3 minutes of reaction at room temperature. The results were expressed using a standard curve prepared with TROLOX (0–200 µmol L^{-1}) as the antioxidant reference. The samples were left to react for 15 minutes and then introduced into a Genesys 30sV spectrophotometer (Thermo Scientific, Waltham, Massachusetts, USA) at a wavelength of 414 nm, reaching an R^2 value of 0.9886. The data were reported as the percentage of free radical inhibition. Finally, the values were calculated using formula (Repo-de-Carrasco and Encina 2008). In this formula, Ai represents the absorbance of the sample (with the free radical), A_0 is the blank absorbance (with added ethanol), and RA corresponds to the reference absorbance (containing the radical and the sample solvent).

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$$Inhibition\ percentage = 1 - \frac{(A_i - A_0)}{RA} \times 100$$

Experimental design and data análisis

The data were analyzed using a comparison of means between treatments. The data obtained were subjected to the statistical program IBM SPSS® version 2020. The database was configured in Microsoft Excel 10 (x64). Comparisons between means were performed, and a Tukey test was conducted with a significance level of (p < 0.05) and respecting one standard deviation between treatments.

RESULTS

Physical quality of pods and yield

All peanut plants produced under conventional systems (without potassium iodide) yielded seeds weighing 0.35 g each, with an average of 2.90 kernels per pod. The evaluated pods measured 3.20 cm in length, and an average of 20 pods per plant was recorded. The incorporation of potassium iodide into the plants resulted in seeds weighing 8-16% more, and the number of kernels per pod increased by 19–36%. Pod size also increased by 0.90 cm when 42 kg ha^{-1} of potassium iodide was applied (Table 1).

Table 1. Comparison of yield and physical quality of peanut seed in plants treated with potassium iodide.

Potassium Iodide (mM L^{-1})	Weight 100 seeds (g)	Grains/Pod	Sheath length (cm)	Pods/Plant^{-1}	Yield/Plant (g)	Yield (kg/ha^{-1})
0.000	35.00 ± 0.22^{c}	2.90 ± 0.04^{c}	3.20 ± 0.04^{b}	20.00 ± 0.41^{c}	22.44 ± 0.28^{c}	2255.00 ± 28.85c
0.050	40.09 ± 1.17^{b}	3.88 ± 0.06^{b}	3.44 ± 0.05^{b}	21.03 ± 0.40^{b}	25.22 ± 0.25^{b}	2422.00 ± 24.00^{b}
0.100	41.77 ± 0.09^{b}	3.80 ± 0.00^{b}	3.57 ± 0.04^{b}	22.89 ± 0.41^{b}	26.99 ± 0.25^{b}	2620.00 ± 24.00^{b}
0.150	42.89 ± 0.08^{b}	4.00 ± 0.05^{a}	4.20 ± 0.05^{a}	24.12 ± 0.40^{a}	27.00 ± 0.25^{a}	2710.00 ± 25.00^{a}
0.200	43.43 ± 0.27^{a}	4.66 ± 0.06^{a}	4.55 ± 0.05^{a}	24.08 ± 0.41^{a}	28.54 ± 0.28^{a}	2889.00 ± 28.70^{a}

Different letters between columns indicate a significant difference between treatments (Tukey p = ≥ 0.05). n = 9 ± standard error.

Photosynthetic pigments in peanut (*Arachis hypogaea* L.) leaves

Table 2 shows the results for chlorophyll a, chlorophyll b, total chlorophyll, and total carotenoids according to the Tukey test at the 0.05% confidence level. The 0.200 mM L^{-1} potassium iodide treatment was significant, with a value of 0.136 mg g^{-1} FW, followed by the control treatment at 0.095 mg g^{-1} FW. The remaining treatments (0.050, 0.100 and 0.150 mM L^{-1}) showed stabilized values of 0.070, 0.073 and 0.074 mg g^{-1} FW, respectively. Organic fertilization based on amino acids was used to obtain these results.

Observing the total carotenoids, the control treatment (0.000 mM L^{-1}) obtained 2.544 mg g^{-1} FW, showing minimal absorption, while the 0.050 mM L^{-1} and 0.100 mM L^{-1} treatments reached 0.032 mg g^{-1} FW and 0.495 mg g^{-1} FW, respectively. The 0.150 mM L^{-1} and 0.200 mM L^{-1} treatments stabilized at 2.451 mg g^{-1} FW and 2.408 mg g^{-1} FW.

Table 2. Average values of chlorophyll a, chlorophyll b, and total carotenoids resulting from the application of potassium iodide at different concentrations.

Potassium iodide ($mM\ L^{-1}$)	Chlorophyll a	Chlorophyll b	Total chlorophylls	Total carotenoids
	mg g^{-1} FW			
	Leaves			
0.000	0.095 ± 0.001^{a}	0.080 ± 0.001^{a}	0.175 ± 0.006^{a}	2.544 ± 0.010^{a}
0.050	0.070 ± 0.001^{b}	0.071 ± 0.002^{ab}	0.141 ± 0.004^{ab}	0.032 ± 0.00a^{b}
0.100	0.073 ± 0.002^{b}	0.070 ± 0.002^{ab}	0.143 ± 0.004^{ab}	0.495 ± 0.008^{ab}
0.150	0.074 ± 0.002^{b}	0.063 ± 0.002^{ab}	0.137 ± 0.004^{ab}	2.451 ± 0.010^{a}
0.200	0.136 ± 0.005^{a}	0.036 ± 0.001^{b}	0.172 ± 0.006^{a}	2.408 ± 0.010^{a}

$mM\ L^{-1}$ = Millimoles per liter. mg g^{-1} FW = Milligrams per gram of fresh weight. Values with the same letters in a column are statistically similar (Tukey; $p \leq 0.05$), n = 9.

Total carbohydrates

The results at potassium iodide concentrations of 0.050 and 0.200 $mM\ L^{-1}$ significantly increased total carbohydrates in 1 g of sample. In contrast, this study obtained 10.00 g of carbohydrates in the control and in the 0.100 $mM\ L^{-1}$ potassium iodide treatment. Additionally, in peanut shells, the concentrations of 0.050 $mM\ L^{-1}$ and 0.200 $mM\ L^{-1}$ resulted in increased carbohydrate content, as shown in Table 3. These outcomes were achieved using organic fertilization based on amino acids.

Table 3. Quantification of total carbohydrates in peanut shells and grain

Potassium iodide ($mM\ L^{-1}$)	Total carbohydrates (g)		
	Shell	Reddish skin	Grain
0.000	10.00 ± 0.22^{a}	10.00 ± 0.23^{a}	10.00 ± 0.22^{a}
0.050	10.00 ± 0.25^{a}	4.89 ± 0.07^{ab}	1.05 ± 0.01^{ab}
0.100	3.80 ± 0.08^{b}	0.07 ± 0.00^{b}	10.00 ± 0.22^{a}
0.150	2.31 ± 0.06^{b}	2.69 ± 0.06^{ab}	2.97 ± 0.08^{ab}
0.200	10.00 ± 0.25^{a}	0.12 ± 0.01^{b}	1.67 ± 0.02^{b}

$mM\ L^{-1}$ = Millimoles per liter. g = Grams. Values with the same letters in a column are statistically similar (Tukey; $p \leq 0.05$). n = 9, ± desviation estandar.

Total anthocyanins

The results for anthocyanins in peanut shells showed that high concentrations of potassium iodide, applied in salt form, produced substantial increases, reaching 16.443 mg g^{-1} FW and 17.172 mg g^{-1} FW. In contrast, the peanut grain accumulated 0.998 mg g^{-1} FW of anthocyanins, which still represents a significant value, as shown in Table 4. These results were obtained using organic fertilization based on amino acids. In contrast, the highest potassium iodide dosage in this research (0.200 mM L-1) resulted in 17.172 mg EA mL FW in red peanut shells-a lower uptake than that reported for the crops mentioned above.

Table 4. Quantification of total anthocyanins in peanut shells and grain.

Potassium iodide (mM L^{-1})	Total anthocyanins (mg EA mL FW)		
	Shell	Reddish skin	Grain
0.000	0.205 ± 0.002^{c}	0.697 ± 0.001^{c}	0.522 ± 0.003^{ab}
0.050	2.091 ± 0.000^{b}	1.584 ± 0.022^{b}	0.269 ± 0.009^{b}
0.100	0.174 ± 0.000^{c}	0.142 ± 0.003^{c}	0.570 ± 0.005^{ab}
0.150	0.649 ± 0.001^{c}	0.586 ± 0.004^{c}	0.427 ± 0.006^{ab}
0.200	16.443 ± 0.022^{a}	17.172 ± 0.030^{a}	0.998 ± 0.006^{a}

mM L^{-1} = Millimoles per liter. mg EA mL FW = Equivalent milligrams of Anthocyanins per milliliter of fresh weight. Values with the same letters in a column are statistically similar (Tukey; $p \leq 0.05$). n = 9, ± desviation estandar.

Antioxidant activity quantification (ABTS+)

The data show that the absolute control achieved the highest percentage of free radical inhibition (96.52%), followed by the 0.050 mM L^{-1} KI treatment, which reached 93.20%. The remaining treatments showed lower percentages of inhibition, which is attributed to the high saturation and accumulation of salts on the leaf surface, as shown in Table 5. Organic fertilization based on amino acids was used to generate these results.

Table 5. Percent of inhibition of the free radical under the ABTS method in shell, reddish skin and peanut grain

Potassium iodide (mM L^{-1})	ABTS free radical inhibition percent (%)		
	Shell	Reddish skin	Grain
0.000	92.03 ± 1.00^{a}	96.52 ± 2.00^{a}	98.04 ± 2.01^{a}
0.050	90.39 ± 1.05^{ab}	92.66 ± 1.00^{b}	96.56 ± 2.00^{ab}
0.100	89.01 ± 0.99^{b}	93.20 ± 1.00^{ab}	94.89 ± 1.01^{ab}
0.150	0 ± 0.00^{c}	0 ± 0.00^{c}	90.98 ± 1.05^{b}
0.200	0 ± 0.001^{c}	0 ± 0.00^{c}	90.02 ± 1.05^{b}

mM L^{-1} = Millimoles per liter. % = Percent. Values with the same letters in a column are statistically similar (Tukey; $p \leq 0.05$). n = 9, ± desviation estandar.

The percentages of free radical inhibition were highest in the control treatment, reaching 96.52%, while potassium iodide contributed to the development of the plants' principal macronutrients.

DISCUSSION

Physical quality of pods and yield

IK fertilization in peanut plantations has shown positive results in both kernel and pod quality. Studies by Ortega-Ramírez *et al*. (2025) and Silva-Marrufo *et al*. (2020) indicate that iodine supplementation does not significantly affect leaf or fruit development; however, it does improve fruit quality, playing a key role in the nutritional attributes of crops and promoting higher yields.

Increasing iodine concentrations does not negatively affect crop production. However, grain quality can be achieved through the agronomic management of these plants (Guerrero-Martin *et al*. 2023).

Photosynthetic pigments in peanut (*Arachis hypogaea* L.) leaves

According to Jarma-Orozco *et al*. (2021), under different sunlight and nitrogen fertilization conditions, *S. rebaudiana* Bert. plants exhibited chlorophyll a, b, and total chlorophyll variations caused by solar radiation, but not by nitrogen levels. In contrast, Budke *et al*. (2021), reported that foliar sprays did not cause physiological damage in apples or pears, as observed in peanut leaves, this suggests that 0.200 mM L^{-1} is the maximum concentration suitable for proper plant development and fruit yield. The report by Silva-Marrufo *et al*. (2025) suggests that high doses of minerals such as Fe and Zn provide chlorophylls up to 35% exposed foliarly.

Rakoczy-Lelek *et al*. (2021), reported carotenoid levels similar to those found in the present study, noting that iodine toxicity was not observed in carrot crops and that no significant statistical differences were detected in their analysis. These findings suggest that iodine applications can enhance physiological activity and support plant development without altering plant morphology or their inherent properties. They also identified several phenolic compounds, reducing sugars, amino acids, tannins, and stable components such as vitamins C and E, carotenoids, and phenolic acids (benzoic and hydroxybenzoic acids). The results at potassium iodide concentrations of 0.050 and 0.200 mM L^{-1} significantly increased total carbohydrates in 1 gram of sample. According to the United States Department of Agriculture (USDA, 2016), 1 gram of raw peanuts contains an average of 16.54 mg EA mL^{-1} FW, dry-roasted peanuts contain 21.3 mg EA mL^{-1} FW, and toasted peanuts contain 15.3 mg EA mL^{-1} FW.

Grain consumption improves human dietary quality (Coe 2020). The intake of reddish peanut skin, which has a high polyphenol content, can contribute to inhibiting carbohydrate pathways in certain foods of interest (Tsujita *et al*. 2014). Compared with the studies by Chávez-Mendoza and Sánchez (2023), who reported values between 51.21 and 61.53% in several bean varieties—where the 'Pinto' variety showed the highest carbohydrate content and the 'Peruano' variety the lowest—the present results ranged between approximately 70 and 80%.

Total anthocyanins

Furthermore, Consentino *et al*. (2023) reported that iodine-biofortified crops present higher anthocyanin and total carbohydrate contents, which differs from Sabatino *et al*. (2021), who indicated that the application of 250 mg L^{-1} of iodine improves the nutritional quality of vegetables and legumes. In the selected peanut shells, a variation was observed at 200 mM L^{-1} compared with the absolute control and the corresponding treatment. Compared with the findings of Broa-Rojas *et al*. (2019), the present study reported a coefficient of variation of 0.47, with a mean of 276 mg g^{-1} FW in pigmented native maize grain, which contains high sugar percentages and is therefore able to generate substantial amounts of anthocyanins. Rabanal-Atalaya and Medina-Hoyo (2022), also reported high anthocyanin values in maize cobs and bracts, with 7.90 mg g^{-1} FW and 4.53 mg g^{-1} FW, respectively—values higher than those obtained in the present research. Other studies have reported concentrations greater than those found here; for instance, Consentino *et al.* (2023)

documented a content of 127.5 mg cyanidin-3-glucoside per 100 g and an iodine dose of 600 mg L^{-1} in strawberries.

Antioxidant activity quantification (ABTS+)

However, several studies have demonstrated the feasibility of enhancing antioxidant capacity through foliar iodine applications. Consequently, the results of the present study surpassed inhibition percentages of 89% in the peel, 93% in the red peel, and 94% in the grain for free radicals in 1 g of sample. Quispe-Herrera *et al*. (2022), reported 96% inhibition of free radicals in the pulp and nectar of ungurahui.

The percentages of free radical inhibition were highest in the control treatment, reaching 96.52%, while potassium iodide contributed to the development of the plants' principal macronutrients. However, several studies have demonstrated the feasibility of enhancing antioxidant capacity through foliar iodine applications. For example, Cortés-Flores *et al*. (2016) reported inhibition values between 89 and 93% at concentrations of 0.015 mM L^{-1}, 0.030 mM L^{-1}, 0.045 mM L^{-1}, and 0.050 mM L^{-1} of iodine - a range associated with high foliar iodine doses that tend to reduce plant height. Similarly, Gonnella *et al*. (2019) observed that exceeding 0.050 mM L^{-1} of potassium iodide can cause toxicological damage in plants, affecting their development, as reported for *Brassica* spp. Medrano-Macías *et al*. (2016) found that iodine additions at 0.100 mM L^{-1} resulted in enzymatic activity levels between 54 and 86% and non-enzymatic antioxidant levels between 22 and 85% in tomato seedlings. Consequently, the results of the present study surpassed inhibition percentages of 89% in the peel, 93% in the red peel, and 94% in the grain for free radicals in 1 gram of sample.

CONCLUSIONS

These effects, together with the use of organic fertilization based on amino acids, favored the quality of the peanut shell and the reddish pigmentation of the skin. Enhancing its nutritional value for human consumption. Furthermore, implementing this technique can reduce dependence on chemical fertilizers promoted during the Green Revolution in Mexico, thereby improving agricultural sustainability and diminishing environmental pollution. The evaluation of peanut crops without nitrogen-fixing bacteria or additional elements becomes relevant, as this case study introduces innovative and sustainable solutions for food production. The application of organic fertilization modified most of the variables studied, however the antioxidant capacity maintained a profile of 90 and 95% activity in peanut grain. Food security remains a global priority, as millions of people still lack access to nutritious and sufficient food to meet their daily needs. In this context, the application of iodine in plants, together with other sustainable agricultural practices, represents a valuable strategy to address this challenge and improve overall quality of life. The findings regarding the effects of iodine and its interaction with nitrogen-fixing bacteria offer a promising starting point for developing innovative, sustainable solutions that can contribute to achieving this goal.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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