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Forage turnip carotenoids for quail egg yolk pigmentation

Carotenoides del nabo forrajero para la pigmentación de la yema del huevo de codorniz

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ABSTRACT

Brassica rapa L. is an alternative source of carotenoids that can be included in animal diets as a natural pigment. Therefore, β-carotene and lutein-zeaxanthin extracted from the leaves, flowers, and seeds of *Brassica* were evaluated in quail egg yolks. The carotenoids were extracted by chemical maceration with HPLC-grade ethanol and incorporated into the quail diet. Lutein-zeaxanthin and β-carotene present in the egg yolk were quantified by HPLC-PAD. In addition, yolk color was evaluated using the DMS method. The effect of the extracts was compared using a completely randomized design with four treatments (three plant parts and one control), three replicates, and five eggs per replicate. The results showed lutein-zeaxanthin contents of 118.05, 9.65, and 11.8 µg/g in leaves, flowers, and seeds, respectively, whereas β-carotene contents were 102.25, 2.85, and 0.20 µg/g, respectively; statistical analysis for both compounds showed higher contents in leaves ($p < 0.05$). Only lutein-zeaxanthin was found in the egg yolk, with values of 40.17, 34.37, and 33.83 µg/g for birds fed with seed, leaf, and flower pigments, with higher content in the treatment with seed extract ($p < 0.05$). In the DMS test, a higher score was observed in birds fed a diet that included seed extract ($p < 0.05$). The results indicate that seed extracts improved yolk pigmentation despite their lower carotenoid content, whereas leaf extracts provided higher carotenoid concentrations but had a lesser effect on yolk color.

Keywords: *Brassica rapa; Coturnix coturnix japonica*; lutein; natural colorants; poultry nutrition; zeaxanthin

RESUMEN

Brassica rapa L. es una fuente alternativa de carotenoides que puede incluirse en la dieta animal como pigmentante natural. Por ello, se evaluaron β-caroteno y luteína-zeaxantina extraídos de hojas, flores y semillas de *Brassica* en yemas de huevo de codorniz. Los carotenoides se extrajeron por maceración química con etanol de grado HPLC e incorporaron en la dieta de codornices. Se cuantificó la luteína-zeaxantina y β-caroteno presentes en la yema de huevo mediante HPLC-PAD. Además, se evaluó el color mediante el método DMS. El efecto de los extractos se comparó con un diseño completamente al azar de cuatro tratamientos (tres partes de la planta y un testigo), 3 repeticiones y 5 huevos por repetición. Los resultados mostraron contenidos de 118,05, 9,65 y 11,8 µg/g de Luteína-Zeaxantina en hojas, flores y semillas, respectivamente, mientras que para los β-carotenos se encontraron valores de 102,25, 2,85 y 0,20 µg/g, respectivamente; el análisis estadístico para ambos compuestos mostró mayor contenido en las hojas ($p < 0{,}05$). En la yema de huevo, solo se encontró luteína-zeaxantina con valores de 40,17, 34,37 y 33,83 µg/g para las aves alimentadas con pigmentos de semillas, hojas y flores, con mayor contenido en el tratamiento con extracto de semillas ($p < 0{,}05$). La prueba DMS presentó un puntaje más alto en las aves alimentadas con inclusión de extracto de semillas ($p < 0{,}05$). Los resultados indican que las semillas mejoran la pigmentación de la yema, pero presentan un bajo contenido de carotenoides, mientras que las hojas muestran un mayor aporte de carotenoides, aunque con un menor efecto sobre el color de la yema de huevo.

Palabras clave: *Brassica rapa*; colorantes naturales; *Coturnix coturnix japonica*; luteína; nutrición avícola; zeaxantina

INTRODUCTION

The food industry uses dyes as food additives to color various food products. Based on their origin, dyes can be classified into two types: synthetic dyes, produced by modifying their chemical or physical structure, and natural dyes, extracted from plant, mineral, and animal sources (Oplatowska-Stachowiak & Elliott, 2017).

For a long time, the food industry has predominantly used artificial dyes as food additives because they offer a wide range of colors required in the final product (Dey & Nagababu, 2022). The color remains very stable during food production processes, as it does not lose any of its nuances or intensity during processing, which makes it easier to work with. In addition, these dyes are more resistant to environmental changes, since they do not disintegrate or change color under different pH conditions or upon exposure to sunlight (Dikshit & Tallapragada, 2018). Likewise, the production costs of these dyes are lower than those of natural dyes, and an important characteristic is their solubility in water, which makes them easier to handle in food (Silva *et al*., 2022).

Despite their recognized benefits, concerns persist about the potential health risks associated with synthetic pigments. Reza *et al*. (2019) showed that high doses (400 mg/kg lw) of carmoisin can cause renal failure and hepatotoxicity and may be linked to hepatic oncogenesis. Other observed effects include allergies, migraines, vision problems, and irritability and hyperactivity in children, which have prompted efforts to determine which artificial pigments are authorized for use in animal feed intended for human consumption and the maximum amount of such dyes in products (Medhi *et al*., 2022; Sadighara *et al*., 2023). However, recent studies have shown that inadequate intake of food products with artificial colors increases the risk of harmful health effects, as consumption of foods containing these additives has risen, leading to additive effects that exceed permitted levels and reduce the effectiveness of measures to mitigate adverse effects.

In contrast, the use of natural dyes is an increasing trend. Studies have shown that these additives possess nutraceutical properties for people who consume them (Khoo *et al*., 2017). Their health benefits include antioxidant potential, improved vision (Eggersdorfer & Wyss, 2018), reduced cardiovascular problems, anticancer effects (Fiedor & Burda, 2014; Woodside *et al*., 2015), antidiabetic effects (Ribeiro *et al*., 2023), and antimicrobial effects (Mitra *et al*., 2021). Among the most commonly used natural additives are carotenoids, which are biological molecules formed from the isoprene units isopentenyl pyrophosphate (IPP) and its isomer, dimethylallyl pyrophosphate (DMAPP), each of which contains five carbon atoms (C5) (Mesquita *et al*., 2017). Their importance lies in their effectiveness in preventing certain human diseases. Vegetables are a source of natural carotenoids and also provide energy nutrients, vitamins, minerals, and antioxidants. Among them is the yellow turnip, a weed plant used for seed production or as food for human and animal consumption (Nisar *et al*., 2015).

A widely used method for extracting carotenoids is chemical maceration, defined as a solid-liquid extraction process in which compounds are transferred from the solid to the extraction liquid (Michelon *et al*., 2012). For the quantification of these compounds, chromatographic techniques such as high-performance liquid chromatography (HPLC) can be used, as they are characterized by their precision in detecting minimal amounts of analytes and by good resolution for compounds of similar polarity (Yeverino, 1997).

The forage turnip belongs to the Brassicaceae family; it is a biennial plant with an axonomorphous root. Many producers consider it fodder, although its leaves are occasionally used as a vegetable (Dejanovic *et al*., 2021). However, its potential has not been developed at an industrial level in the region, and there is evidence of a lack of interest in alternative uses. The characteristic yellow color of the flower indicates the presence of carotenoids in its chemical composition, a factor that is important when assessing its potential as a natural dye. Similarly, the leaves and seeds are usually used as raw materials for obtaining the dyes, so they are included in the study.

On the other hand, the poultry industry has encouraged the use of dyes as additives in animal feed, especially in diets intended for egg production. This is intended to improve the product's visual presentation at the time of consumption, as studies show a greater consumer preference for eggs with intensely colored yolks than for those with paler colors (Sözcü, 2019). In addition, the benefits described in the previous paragraphs increase the acceptability of coloring the yolk with this type of natural substance.

Based on the above, the present study aimed to extract carotenoids from the flowers, leaves, and seeds of forage turnips and to evaluate their effect on quail egg yolk pigmentation.

MATERIALS AND METHODS

The study was conducted at the Botana Experimental Farm, located southwest of Pasto at an elevation of 2,800 meters above sea level, with an average temperature of 12 °C and a relative humidity of 75%. The analyses were conducted in the specialized laboratories of the University of Nariño and at the Biota Group's research center at the same university.

Plants

The yellow turnip required for the study was grown at the Botana Experimental Farm, and the researchers waited for it to flower and produce seeds before harvesting it. The collection and pretreatment of the plant material followed the methodology proposed by Cornejo and Tita (2011). A total of 2 kg of leaves, 2 kg of flowers, and 5 kg of yellow turnip seeds were used. Each material was collected separately in properly labeled plastic bags. The samples were transported in a polystyrene cooler with cooling gel at 4 °C to the Biota Research Group laboratory. For the analysis, leaves in the best condition—without breaks, with an intense green color, and without visible degradation on their surface—were selected and chopped into smaller pieces before processing. The flowers were cut from their stems; those that were clean and free of pests (aphids) were selected and reduced in size for processing. Finally, the seeds were sieved to remove scale from the pod; those in poor condition were removed and ground to obtain powder, allowing better extraction of the carotenoids. All samples were processed immediately after chopping or grinding to avoid any loss of carotenoids.

Extraction of Carotenoids from Turnip (Brassica rapa **L.***)*

The procedure followed the methodology of Cornejo and Tita (2011). For every 3 g of plant material (leaves, flowers, or seeds), 12 mL of HPLC-grade ethanol was added. The samples were placed in beakers covered with aluminum foil and left to stand for two hours, then filtered to separate the solid from the solvent. This process was repeated until the plant material showed no further color loss. In each extraction, the presence of pigments was verified by thin-layer chromatography (TLC). After all extractions were completed, the extract was evaporated to dryness using a rotatory evaporator.

HPLC-PAD Quantification of Carotenoids in Turnip (Brassica rapa* L.*)

The method of Zaccari *et al*. (2012) was used with some modifications. The pigmented extracts were pooled and quantified using an HPLC-PAD system (Waters Breeze HPLC Liquid Chromatograph, Binary Pump 1525) equipped with a Hypersil Gold Thermo Scientific C18 column (250 mm × 4.6 mm × 3.5 µm) at 30 °C, with a mobile phase of methanol: acetonitrile and a flow rate of 1 mL/min. A Waters 2998 PDA detector was used at 440, 450, and 480 nm (scan from 200 to 700 nm), along with a Rheodyne 7725I injector with a 20 µL loop. Analytical standards were used for quantification to determine total carotenoids (TC), β-carotene, lutein, and zeaxanthin. To determine the retention times and absorption spectra of the pigment standards (β-carotene, lutein, and zeaxanthin), the wavelength value used by Mondragón (2006) was taken as a reference, i.e., 450 nm for lutein and β-carotene, and, since zeaxanthin has a molecular structure similar to that of lutein, the same wavelength was used.

Determination of Carotenoids for Delivery to Birds

After quantifying carotenoids in leaves, flowers, and turnip seeds, the amount of plant material to be used for bird feeding was determined. For extraction, the required amounts of plant material were weighed, ethanol was used as a solvent in sufficient quantity to completely cover the samples, and 5-L glass jars were used as maceration containers. The samples were left for 24 hours in a dark place to avoid light-induced carotenoid degradation. After this time, the samples were filtered through canvas to separate the solvent from the macerated material. This process was repeated until the solid residue was discolored. The extract from each extraction was evaporated under vacuum using a rotary evaporator at 40 °C and 35-40 rpm. At the end of the extractions, the total volume of extract was evaporated to dryness using a rotary evaporator to prepare it for incorporation into the poultry feed.

Quail Feeding

A total of 120 35-day-old female quails of the *Coturnix coturnix japonica* line from Valle del Cauca were used. The birds were kept at the Botana Experimental Farm until they were confirmed to be in peak condition, after which egg collection began. For bird management, there were six cages, each divided into two compartments, for a total of 12 compartments, with a capacity of 10 quails per compartment. Feeders and drinkers were provided in each cage. A commercially balanced feed with 23% protein and enriched with turnip carotenoids was used for the quail. Each quail received 27 g of feed per day, divided into three portions (7:00, 13:00, and 17:00), with water available ad libitum. The birds underwent a 15-day adaptation period to the balanced feed; thereafter, feeding continued for 21 more days so that the birds could assimilate the pigment and its effect on egg yolk color could be observed. Three treatments plus one control were used, each with a carotenoid inclusion level derived from different parts of the turnip plant (leaves, flowers, and seeds). In this study, 25 mg of carotenoids were added per kg of balanced feed according to the treatment. The control treatment was designated as T0 (without the addition of carotenoids), T1 (with the addition of leaf extract), T2 (with the addition of flower extract), and T3 (with the addition of seed extract).

Extraction of Carotenoids from Egg Yolk and Quantification by HPLC-PAD

After a 9-day adaptation and ration assimilation period, 15 eggs were randomly selected per treatment, for a total of 60 eggs. For each egg, the yolk was manually separated from the egg white. The yolk was homogenized, and 1.5 g was transferred into a test tube using a pipette. Then, 10 mL of HPLC-grade acetone was added, and the mixture was stirred until homogenized and then left to stand in the dark for 12 hours. After this time, the supernatant was collected using a pipette and subjected to rotary evaporation at room temperature and 30 RPM until dryness. Finally, the samples were dissolved in 1,000 µL of ethyl acetate for subsequent quantification and analysis by HPLC-PAD. For each treatment, the process was performed in triplicate.

Evaluation of Egg Yolk Color by the DMS Method

The yolk color of another group of eggs was measured using the DSM YolkFan™ color scale. Twenty-four eggs were randomly selected for each treatment. The yolks were placed on Petri dishes in an illuminated area and visually compared with the fan to determine the closest color. The corresponding value on the scale (1-16) was recorded for each sample.

Statistical Analysis

A completely randomized design was used with four dietary treatments (including the control) and three replicates per treatment. Each replicate consisted of a group of ten animals, from which 15 eggs were sampled per treatment, yielding a total of 60 eggs (the egg served as the experimental unit for quality analysis). For yolk color evaluation using the DSM fan, six eggs per treatment were randomly selected under the same experimental design. Data were subjected to one-way analysis of variance (ANOVA). Before the ANOVA, the assumptions of normality and homogeneity of variances were verified using the Shapiro-Wilk and Levene's tests, respectively. When significant differences were detected, means were compared using Tukey's Honestly Significant Difference (HSD) post hoc test at a 95% confidence level ($p < 0.05$). Data were collected and organized in Microsoft Excel for Windows® and analyzed in the statistical package Statgraphics Plus 5.1®.

RESULTS

Table 1 shows the results obtained from the quantification of total carotenoids, lutein, and zeaxanthin extracted from the different parts of the forage turnip. The lutein and zeaxanthin carotenoids were quantified as a mixture (lutein-zeaxanthin) since their chromatographic peaks overlapped and had very similar retention times. The statistical analysis showed that the three plant parts differed in the total carotenoids, with a higher content in leaves, followed by flowers and, finally, seeds ($p < 0.05$).

Table 1. *Quantification of total carotenoids (TC) and lutein-zeaxanthin*

Part of the plant	L-Z (µg/g)	C_T (µg/g)
Leaves	118.05 a	625.20 a
Flowers	9.65 b	312.90 b
Seeds	11.80 b	13.60 c
SEM	0.232	5.03

Note. L-Z: *Lutein* and *Zeaxanthin*. CT: Total carotenoids. SEM: Standard Error of the Mean. Means in the same column with different superscripts (a, b, c) differ significantly according to Tukey's Honestly Significant Difference (HSD) test ($p < 0.05$).

Statistically significant differences were observed in the lutein and zeaxanthin content ($p < 0.05$, Table 1). As observed for total carotenoids, a higher content of this substance was found in the leaves, although flowers and seeds presented similar contents. The values reported in Table 1 show that the differences in the Lutein-Zeaxanthin content are substantial when comparing the leaves with the other parts of the plant (flowers and seeds).

For flowers and seeds, the measured contents fall at the lower end of the range reported by Reif *et al*. (2013). This indicates that their contents are lower than those in the leaves, underscoring the limited potential of these plant parts for dye extraction. Studies on calendula have shown a high lutein content in the flower, with values exceeding 800 µg/g, a figure that is very high compared with that found in forage turnip (Bhattacharyya *et al*., 2010). This indicates the low capacity of the forage turnip flower to contribute pigment; therefore, extracting lutein from the flower would require a large quantity of flowers to obtain a significant amount for use in animal feed. For the seed, the literature does not report on it, so the results cannot be compared with other studies. However, based on reports regarding the leaves and flowers, it can be inferred that the seeds have a low lutein content and, therefore, provide a very small amount of this substance for use as a natural pigment.

On the other hand, Table 2 shows the results obtained for β–carotene content in the different parts of the forage turnip.

Table 2. β-*carotene content in the different parts of the forage turnip*

Part of the plant	β – carotene(µg/g)
Leaves	102.25 ± 0.191
Flowers	2.85 ± 0.015
Seeds	0.20 ± 0.001

Note. Mean ± SEM: Standard Error of the Mean

Carotenoids in Quail Egg Yolks

When identifying carotenoids in quail egg yolks, only lutein and zeaxanthin (L-Z) could be quantified, whereas β-carotene was not detected in any of the samples, as shown in Figure 1 and Table 3. The results indicated that quail egg yolks fed carotenoids extracted from forage turnip seed had higher L-Z content, followed by treatments with leaves and flowers; the treatment without pigment addition had the lowest content ($p < 0.05$).

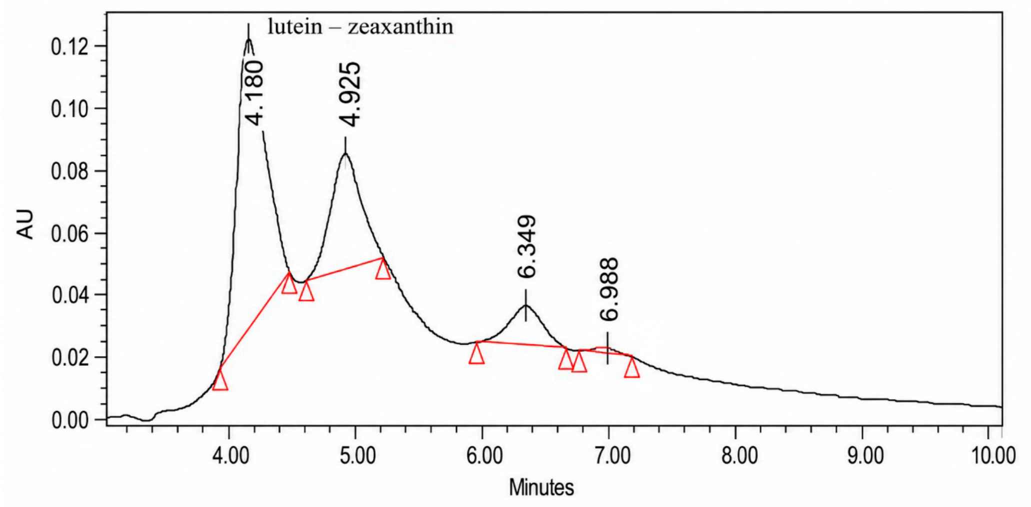

Figure 1. *Chromatogram of carotenoids in quail egg yolk, at 450 nm*

Table 3. *Quantification of lutein-zeaxanthin in the yolk of quail eggs*

Treatment	Dye	Lutein-zeaxanthin content(µg/g)
T3	Seeds	40.17 a
T1	Leaves	34.37 b
T2	Flowers	33.83 b
T0	Without Dye	29.83 c
SEM	----	0.430

Note. SEM: Standard Error of the Mean. Means in the same column with different superscripts (a, b, c) differ significantly according to Tukey's Honestly Significant Difference (HSD) test ($p < 0.05$).

Evaluation of Pigmentation in Quail Egg Yolks

For yolk pigmentation, the T3 treatment supplemented with seed extract showed a higher value than the other two treatments and the control treatment ($p < 0.05$), obtaining a score of 12.80, close to 13, which corresponds to yellow-orange coloration. This value was higher than that of the control treatment (T0), which had a value close to 11, corresponding to an intense yellow coloration on the DSM color fan. The mean yolk pigmentation values for all treatments are presented in Table 4.

Table 4. *DSM evaluation for yolk coloration*

Treatment	Dye	DSM
T3	Seeds	12.80 a
T1	Leaves	10.80 b
T2	Flowers	10.67 b
T0	Without Dye	8.73 c
SEM	---	0.256

Note. SEM: Standard Error of the Mean. Means in the same column with different superscripts (a, b, c) differ significantly according to Tukey's Honestly Significant Difference (HSD) test ($p < 0.05$).

DISCUSSION

Carotenoids in Forage Turnip

The lutein–zeaxanthin (118.05 µg/g) and β-carotene (102.25 µg/g) concentrations detected in forage turnip (*Brassica rapa* L.) leaves substantially exceeded those previously reported for members of the Brassicaceae family. In this regard, Dias *et al*. (2009) reported lutein and β-carotene concentrations of 56 µg/g and 44 µg/g, respectively, in the leaves of *Brassica rapa* L. var. *rapa*. Similarly, Reif *et al*. (2013) reported lutein concentrations ranging from 38 to 105 µg/g across leaves of different *Brassica* species, whereas Ashfaq *et al*. (2020) found considerably lower β-carotene levels in cabbage (6.0 µg/g), cauliflower (5.0 µg/g), and radish leaves (5.2 µg/g). This pronounced disparity highlights the intrinsic variability within the Brassicaceae family; however, the carotenoid profile observed in forage turnip lies at the upper end of this variability spectrum. From an analytical perspective, the elevated dihydroxy-xanthophyll fraction reported in the present study can be attributed to the chromatographic co-elution of lutein and zeaxanthin, which were quantified as a combined fraction owing to the proximity of their retention times. Consequently, the nominal concentration is expected to be higher than the values reported in studies where both analytes were resolved and quantified separately. Furthermore, agronomic and physiological factors likely contributed to these differences. The plants evaluated belonged to distinct cultivars and were subjected to specific environmental conditions, soil characteristics, fertilization regimes, phenological stages, and harvest periods, all of which are known to dynamically modulate isoprenoid biosynthesis pathways. In contrast, carotenoid concentrations in flowers and seeds were at the lower end of the range reported by Reif *et al*. (2013). The relatively low pigment concentration in flowers, compared with that in other botanical matrices such as marigold (*Calendula officinalis*), which may contain more than 800 µg/g of carotenoids (Bhattacharyya *et al*., 2010), suggests a limited capacity for pigment biosynthesis and/or accumulation in this floral structure. Although this finding may partially reflect the lower extraction efficiency of ethanolic solvents in dense matrices such as seeds, the results also point toward an underlying biological constraint associated with genotype-dependent carotenoid metabolism.

Egg Yolk Pigmentation

Despite the low baseline carotenoid concentration in forage turnip seeds, their dietary inclusion (Treatment T3) resulted in the highest lutein–zeaxanthin concentration in egg yolk (40.17 µg/g) and the most intense pigmentation according to the DSM Yolk Color Fan (12.80; yellow-orange), surpassing both leaf-derived extracts (T1: 34.37 µg/g; DSM: 10.80) and flower-derived extracts (T2: 33.83 µg/g; DSM: 10.67). All pigment-supplemented treatments showed higher values than the basal control (T0: 29.83 µg/g; DSM: 8.73). This response can be explained by the digestive and metabolic physiology of laying quails. Dihydroxy-xanthophylls, particularly lutein and zeaxanthin, are efficiently absorbed in the intestine, incorporated into circulating lipoproteins, and selectively deposited within the lipid-rich yolk matrix. Their hydroxyl functional groups confer greater polarity, enhancing transport, micellar incorporation, and tissue deposition relative to monohydroxylated xanthophylls or epoxidized carotenes (Dumbrava *et al*., 2006). In contrast, hydrocarbon carotenes such as β-carotene, which were not detected in the analyzed yolks, contribute minimally to egg pigmentation because of their limited deposition in plasma and ovarian tissues (Ramos-Mamani, 2014). Instead, these compounds are preferentially diverted toward systemic physiological functions, particularly their conversion into vitamin A to satisfy essential metabolic and immunological requirements. Using HPLC analysis, Sinanoglou *et al*. (2011) confirmed this phenomenon by reporting the complete absence of β-carotene in quail egg yolks, with only xanthophylls (zeaxanthin, lutein, canthaxanthin, and cryptoxanthin) being detected. The superior pigment transfer observed with the seed extract treatment (T3) suggests that the lipid microenvironment or intrinsic matrix characteristics of forage turnip seeds enhanced xanthophyll micellarization and intestinal bioaccessibility. The lutein–zeaxanthin concentrations obtained in the present study were markedly higher than those reported by Islam and Schweigert (2015), who quantified 4.86 µg/g of lutein and 1.85 µg/g of zeaxanthin in eggs from conventional feeding systems. Moreover, the values exceeded those reported by Karadas *et al*. (2006), who achieved yolk concentrations of 28.57 µg/g of lutein and 2.72 µg/g of zeaxanthin using commercial marigold and tomato extracts. Likewise, the colorimetric response observed on the DSM scale is consistent with the findings of Romero *et al*. (2022), who achieved a score of 12.4 through direct supplementation with 405 mg/kg of synthetic lutein, resulting in 15.73 µg/g in fresh yolk. Similar chromatic enhancement trends have also been reported following the inclusion of alternative botanical pigment sources such as *Moringa oleifera* (Degollado-Aguayo, 2018), amaranth meal (*Amaranthus* spp.) (Imbaquingo, 2020), and 20% *Wolffia arrhiza* meal (Suppadit *et al*., 2012).

CONCLUSIONS

The findings of the present study demonstrate that forage turnip (*Brassica rapa* L.) is a promising natural source of carotenoids for poultry nutrition and egg yolk pigmentation. Although leaves exhibited the highest concentrations of lutein–zeaxanthin and β-carotene, their use in carotenoid extraction must account for the pronounced susceptibility of these compounds to post-harvest oxidative degradation, which can cause substantial pigment losses unless biomass is preserved under stringent conditions, including refrigeration, light exclusion, controlled atmospheres, and preferably lyophilization. This limitation is expected to be even more critical in floral tissues due to their greater physiological sensitivity and lower pigment stability. Conversely, despite their comparatively lower carotenoid content, seeds resulted in the highest lutein–zeaxanthin deposition and yolk pigmentation response, suggesting enhanced carotenoid bioaccessibility, micellarization efficiency, and metabolic utilization by laying birds. From both zootechnical and industrial perspectives, seeds therefore emerge as the most promising fraction, as they can be readily conditioned, stored, and incorporated directly into poultry diets while simultaneously contributing nutritional value and pigmentation potential. Consequently, these results should be regarded as a preliminary step toward understanding the functional potential of forage turnip-derived carotenoids and warrant further investigation into carotenoid stability during post-harvest handling, optimization of preservation strategies, and the nutritional and economic feasibility of incorporating forage turnip seeds as a natural pigment source and functional feed ingredient in commercial poultry production systems.

AUTHOR CONTRIBUTIONS

Conceptualization, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Methodology, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Software, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Validation, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Formal Analysis, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Investigation, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Resources, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Data Curation, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Writing—Original Draft Preparation, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Writing—Review & Editing, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Visualization, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Supervision, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Project Administration, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.; Funding Acquisition, D.N.O.-B., A.A.O.-P., A.J.M.-G., J.J.P.-S., and O.L.B.-C.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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