

Research Paper

Hyoseris radiata L. as a novel salad crop: yield and chemical characterization of hydroponically grown microgreens and baby leaves

Stefania Truschi^a, Alfonso Crisci^b, Piero Bruschi^{a,*}, Ada Baldi^a, Lorenzo Marini^a, Tania Martellini^c, Alessandra Cincinelli^c, Anna Lenzi^a

^a Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Piazzale delle Cascine 18, Florence, 50144, Italy

^b IBE CNR, Institute for Bioeconomy, Via Madonna del Piano 10, Sesto Fiorentino, Florence, 50019, Italy

^c Department of Chemistry 'Ugo Schiff' (DICUS), University of Florence, Via della Lastruccia 3-13, Sesto Fiorentino, Florence, 50019, Italy

ARTICLE INFO

Keywords:

Hyoseris radiata L.
Wild edible plants
Leafy vegetables
Hydroponics
Nutrient content
Estimated dietary intake
Health risk index

ABSTRACT

Hyoseris radiata L., a Mediterranean wild edible species (WEP), was evaluated for the first time under hydroponic cultivation as microgreens and baby leaves. Plants were grown from wild-collected seeds using full- or half-strength Hoagland nutrient solutions (H and H/2). Growth and yield were assessed at each developmental stage, while chemical composition was analyzed across all stage × nutrient combinations. Wild plants were also analyzed as a reference for comparison. No significant differences in growth or yield were observed between H and H/2 treatments, suggesting the feasibility of reducing nutrient inputs for the hydroponic cultivation of this species without compromising productivity. Chemical composition was generally consistent with that reported for other leafy WEPs and vegetables. PCA clearly separated microgreens, baby leaves, and wild plants. Wild samples showed higher concentrations of phenols, flavonoids, soluble sugars, and iron, and substantially lower nitrate levels than cultivated plants. Baby leaves were characterized by higher chlorophyll content, vitamin B6, vitamin C, and iron than microgreens. The overlap between H and H/2 treatments indicated that developmental stage had a stronger influence on chemical composition than nutrient solution strength. Based on EDI%, cultivated *H. radiata*, especially baby leaves, proved to be a valuable source of vitamin A, vitamin B9, iron, and molybdenum. No concerns related to heavy metal accumulation were detected. Nitrate concentrations were higher in cultivated plants but were significantly reduced in baby leaves grown under H/2. Overall, *H. radiata* showed good productivity under reduced nutrient supply and promising nutritional quality, supporting its potential as a novel hydroponically grown leafy vegetable.

1. Introduction

The growing consumer demand for diverse, nutritious, and sustainably produced fresh vegetables has intensified interest in the identification of novel crops that combine health-promoting attributes with agronomic potential. In this context, wild edible plants (WEPs) have attracted renewed attention as underexploited resources for functional foods and sustainable food systems (Vignesh et al., 2024).

Wild edible plants (WEPs), once central to human diets, have progressively declined in use following the transition to agriculture, during which domesticated crops became predominant (Carvalho et al., 2016). Nevertheless, they continue to play an important role in many cultures due to their nutritional value and sociocultural significance (Groot et al., 2002; Pardo-de-Santayana et al., 2007; Schulp et al., 2014).

Ethnobotanical studies have documented a rich diversity of WEPs consumed in the Mediterranean diet, with a predominance of leafy species used in salads, soups, and cooked dishes (Baldi et al., 2022). Leafy WEPs are known to be rich in phytochemicals with antioxidant effects (Barros et al., 2016), and are also valuable sources of proteins, vitamins, sugars, and minerals (Sánchez-Mata et al., 2016; García-Herrera et al., 2016). The chemical profile of leafy WEPs highlights their potential as functional food sources and supports their valorization as novel crops for modern agricultural systems. As the edible portion consists of young leaves (Baldi et al., 2022), the production of leafy WEPs as specialty salad products, such as microgreens and baby leaves, appears particularly promising. Microgreens are seedlings harvested at around 5 cm in height, when the cotyledons are fully expanded and the first pair of true leaves is more or less developed

* Corresponding author.

E-mail address: piero.bruschi@unifi.it (P. Bruschi).

<https://doi.org/10.1016/j.scienta.2026.115126>

Received 22 June 2026; Received in revised form 11 August 2026; Accepted 24 August 2026

Available online 28 August 2026

0304-4238/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

(Lenzi et al., 2019). Baby leaves are also harvested before reaching full maturity, but they are older and larger than microgreens (approximately 10 cm in height) (Treadwell et al., 2020). Both products are increasingly appreciated for their sensory quality, ease of consumption, and high concentration of health-promoting compounds.

Hydroponic systems enable the production of high-quality leafy vegetables under controlled conditions, representing a suitable cultivation method for the valorization of WEPs. These systems mitigate soil degradation, water scarcity, and climate variability, while ensuring yield consistency, product safety, and the efficient use of resources such as water and nutrients (Verma et al., 2024). Recent studies have demonstrated the feasibility of using hydroponic systems to grow WEPs as microgreens and/or baby leaves (Lenzi et al., 2019; Puccinelli et al., 2021; Baldi et al., 2023).

Comprehensive ethnobotanical surveys in the Mediterranean Basin highlight the strong tradition of WEPs use in Italy, with regions such as Apulia, Sicily, and Tuscany reporting the highest number of recorded taxa (Paura et al., 2021; Baldi et al., 2022). *Hyoseris radiata* L., commonly referred to as “wild chicory”, is a Mediterranean leafy WEP that has been traditionally consumed across several Italian regions. Its young leaves are commonly utilized either raw or cooked in a variety of local culinary preparations (Guarrera and Savo, 2016; Geraci et al., 2018; Sicari et al., 2020). The leaves present a slight bitter taste and are highly appreciated for their softness as demonstrated in sensory panel tests (Benvenuti et al., 2017). Beyond its gastronomic use, this species has a documented history in traditional medicine, where it has been employed for its diuretic, depurative, and litholytic properties (Guarrera, 2006). Phytochemical investigations have identified the presence of bioactive compounds, including triterpenes and phenolic constituents, which are associated with antioxidant activity (El-Masry et al., 1983; Vanzani et al., 2011; Sicari et al., 2020; Vitiello et al., 2024). Given its long-standing culinary relevance and recognized nutraceutical potential, *H. radiata* represents a promising candidate for development as a novel salad crop. However, this species remains largely underexplored in terms of domestication and cultivation. A preliminary cultivation attempt was reported by Benvenuti et al., 2017, who grew *H. radiata* in alveolar polystyrene trays filled with a peat-perlite substrate supplemented with a controlled-release fertilizer. The present study aimed to assess, for the first time, the suitability of *H. radiata* for hydroponic cultivation as microgreens and baby leaves. With this aim, growth performance, yield, and nutritional and health-related traits of plants hydroponically grown from wild-collected seeds under two nutrient solution strengths were evaluated. Furthermore, the contribution of the obtained products to dietary nutrient intake and their potential health risks associated with nitrate and trace element accumulation were assessed. Wild-harvested plants from the same seed collection site were also analysed as a benchmark for the chemical profile.

2. Materials and methods

2.1. Plant material, growing conditions, and growth parameters

Hyoseris radiata baby leaves and microgreens were grown hydroponically in a floating system using seeds collected from wild populations located in Cercina, Tuscany, Italy (43°50'43" N, 11°15'45" E; ~350 m a.s.l.) in spring 2023. The area is located on the hills north of Florence and is characterized by a sub-Mediterranean hill climate, with mild temperatures and relatively high humidity. Soils are typically loamy to clay-loam, moderately alkaline, and exhibit low electrical conductivity.

Seeds (germination rate: 98%) were sown in polystyrene cell trays (22.75 × 13.08 cm; 28 cells, Ø 0.27 cm) filled with vermiculite (Perlite Italiana Srl, Corsico, Milan, Italy) at densities of 1640 and 14,400 seeds m⁻² for baby leaves and microgreens, respectively. After sowing, trays were maintained in darkness at 20 °C for 48 h and then transferred to

polyethylene terephthalate tanks (26 × 18 × 8 cm) containing 1.8 L of full- (H) or half-strength (H/2) Hoagland nutrient solution. Nutrient solutions were prepared using distilled water to eliminate initial mineral background. The full-strength solution was composed as follows (mg L⁻¹): Ca(NO₃)₂ × 4H₂O (1180), KNO₃ (505), KH₂PO₄ (136), MgSO₄ × 7H₂O (493), Fe-EDDHA (46.6), H₃BO₃ (2.86), MnCl₂ × 4H₂O (1.81), ZnSO₄ × 7H₂O (0.22), CuSO₄ × 7H₂O (0.08), Na₂MoO₄ × 2H₂O (0.03). The full-strength Hoagland solution showed an EC of 1.7 dS m⁻¹ and a pH of 5.8, while the half-strength solution exhibited an EC of 1.1 dS m⁻¹ and a pH of 5.9. Eighteen tanks were used for each stage × nutrient solution combination and were randomly assigned within a walk-in growth chamber. Each tank corresponded to one replicate. To minimize positional effects, tanks were rotated every week during cultivation. Plants were grown under controlled conditions (22 ± 1 °C; 16 h light/8 h dark; average PPFD of 80 µmol m⁻² s⁻¹, corresponding to an estimated DLI of 4.6 mol m⁻² day⁻¹). During the trial, tanks were refilled back to their initial level with fresh nutrient solution at the original concentration whenever the liquid was nearly depleted. Active aeration of the nutrient solution was not provided; however, adequate root zone oxygenation was sustained by passive diffusion due to the shallow solution depth, the short cultivation cycle, and frequent solution replenishment.

Plants were harvested at the microgreen or baby leaf stage (defined in the Introduction), which, under the conditions of this study, corresponded to 2 and 6 weeks after sowing, respectively. For microgreens, fresh weight (FW), dry weight (DW; oven-dried at 80 °C until constant weight), and leaf area (LA; LI-3100 area meter, LI-COR, Lincoln, NE, USA) were determined. For baby leaves, measurements included number of leaves, maximum leaf length, FW, DW, and LA. Growth parameters were measured on three plantlets for each tank. Yield was calculated based on the production obtained from each tray and normalized to a per m² basis. Fresh leaf samples were collected from each tank and stored at -20 °C prior to chemical analyses.

Wild reference plants (18 samples) were collected at the basal rosette stage from the same site and on the same date as seeds.

2.2. Chemical analyses

Chemical determinations were performed on 18 biological replicates for each stage × nutrient solution combination in hydroponically grown plants, and on 18 independent replicates of wild-harvested plants. Quality assurance and quality control procedures were applied to all analytical determinations to ensure data reliability and reproducibility. Procedural blanks and certified reference standards were included in each analytical batch. Calibration curves were accepted only when R² ≥ 0.995. Replicate analyses were performed and results were expressed as mean value. Limits of detection (LOD) and quantification (LOQ) were determined according to method-specific criteria. All results are expressed on a fresh weight basis.

2.2.1. Chlorophylls and carotenoids

Chlorophylls and carotenoids were determined spectrophotometrically by UV-VIS analysis following methods adapted for leafy vegetables (Song et al., 2020). Briefly, 0.5 g of leaves were extracted in an acetone/alcohol mixture (1:1, v/v); chlorophyll *a*, chlorophyll *b*, and total carotenoids contents were quantified at 663, 645, and 440 nm, respectively.

2.2.2. Total phenolics and flavonoids

Total phenolic content was determined using the Folin-Ciocalteu colorimetric assay and expressed as gallic acid equivalents (GAE) (Tadolini et al., 2000). Briefly, 1 g of fresh leaves was pulverized under liquid nitrogen and extracted in 8 mL of 80% methanol in a boiling water bath for 60 min. Extracts were centrifuged at 12,000 rpm for 10 min, concentrated under reduced pressure at 40 °C, reconstituted with distilled water, and centrifuged again at 8000 rpm for 20 min. An aliquot

(1 mL) of the supernatant was mixed with distilled water, Folin–Ciocalteu reagent, and 26.7% sodium carbonate solution. Absorbance was measured at 760 nm. Total flavonoids were determined by the aluminum chloride colorimetric method and quantified spectrophotometrically at 510 nm using quercetin as reference standard. Results were expressed as mg quercetin equivalents per kg fresh weight.

2.2.3. Antioxidant capacity

Antioxidant capacity was evaluated using the ferric-reducing antioxidant power (FRAP) assay according to [Benzie and Strain \(1996\)](#). Extracts obtained for phenolic determination were mixed with FRAP reagent (0.3 mol L⁻¹ acetate buffer, 10 mmol L⁻¹ TPTZ, and 20 mmol L⁻¹ FeCl₃ in a 10:1:1 ratio) and incubated at 37 °C for 10 min. Absorbance was measured at 593 nm.

2.2.4. Proteins

Total proteins were quantified as total nitrogen multiplied by 6.25 (N × 6.25) according to ISTISAN 96/34 of Nutritional Institute of Health (ISS) ([Baldini et al., 1996](#)).

2.2.5. Soluble sugars

Total soluble sugars were determined by HPLC–UV following ISTISAN analytical methods for food analysis. Briefly, soluble sugars were extracted by sonication using a mixture of acetonitrile and water (60:40, v/v) and subsequently analysed by HPLC–UV at 190 nm.

2.2.6. Vitamins

Given the low lipid content of leafy matrices, water-soluble vitamins (vitamins B1, B2, B3, B5, B6, B9, and C) were determined using an extraction procedure suitable for low-fat food matrices. Samples were extracted with 0.2% phosphoric acid and analyzed by HPLC–UV using an Eclipse Plus C18 column and a gradient elution system (solvent A: phosphate buffer pH 7, water 1:10 v/v; solvent B: acetonitrile). Quantification was performed using external calibration curves, with an internal standard applied to correct for recovery. Different detection wavelengths were used for each vitamin: vitamin B1 (232 nm), vitamin B2 (268 nm), vitamin B3 (214 nm), vitamin B5 (205 nm), vitamin B6 (220 nm), vitamin B9 (280 nm), and vitamin C (266 nm). Vitamin A, expressed as retinol activity equivalents (RAE), was determined according to [Raju et al., 2007](#).

2.2.7. Major and trace elements

Elemental analysis of major minerals (Ca, P, Mg, Na, K), essential trace elements (Fe, Mn, Zn, Cu, Mo, Se), and non-essential trace elements (Al, Cr, Ni, As, Cd, Sb, Pb) was performed after microwave-assisted acid digestion according to [European Committee for Standardization \(2014\)](#). Quantification was carried out by ICP-MS following [International Organization for Standardization \(2016\)](#). Briefly, homogenized samples were mineralized in closed-vessel microwave systems using nitric acid. Digests were diluted to volume with ultrapure water and analyzed by ICP-MS. Calibration was performed using multi-element standard solutions; procedural blanks and quality control samples were included in each analytical batch.

2.2.8. Nitrate

Approximately 3 g of homogenized fresh samples were extracted with 20 mL of ultrapure water. Separation was achieved on an anion-exchange column coupled with suppressed conductivity detection. The lowest calibration level was 0.5 mg L⁻¹ (expressed as NO₃⁻), corresponding to a limit of quantification (LOQ) of approximately 3 mg kg⁻¹ fresh weight under the applied operating conditions. Calibration standards were verified in each analytical session, and procedural blank samples consistently showed no detectable nitrate contamination.

2.3. Contribution to nutrient dietary intake

The estimated dietary intake (EDI, mg day⁻¹) of vitamins (A, C, B2, B3, B6, B9) and essential mineral elements (Ca, K, Mg, Na, P, Cu, Fe, Mn, Mo, Zn) possibly resulting from the consumption of microgreens or baby leaves of *H. radiata* was calculated by the following formula:

$$EDI = C \times (CP / 1000)$$

where C is the mean concentration of the nutrient (mg kg⁻¹ FW) in the produce, averaged across the two solution treatments, and CP is the daily consumption rate per person, assumed to be 20 g for microgreens ([Lenzi et al., 2019](#)) and 50 g for baby leaves ([Elgueta et al., 2019](#)).

To evaluate the contribution of microgreens and baby leaves to human vitamin and mineral requirements, EDI was expressed as percentage (EDI%) of the Population Reference Intake (PRI, mg day⁻¹ or µg day⁻¹), Adequate Intake (AI, mg/day⁻¹), or Suggested Dietary Target (SDT, mg day⁻¹) according to the LARN (V revision) issued by the *Società Italiana di Nutrizione Umana* ([Società Italiana di Nutrizione Umana \(2024\)](#)).

2.4. Health risk assessment

To assess the potential health risks associated with the consumption of *H. radiata* microgreens and baby leaves, the Health Risk Index (HRI) was calculated for selected toxic and potentially toxic elements (As, Cd, Cr, Mn, Mo, Ni, Sb, and Zn) and nitrate detected in these products. For toxic elements, the following formula was used:

$$HRI = EDI_{BW} / RfD$$

where EDI_{BW} is the estimated dietary intake (EDI, mg day⁻¹) normalized per kg of body weight (BW), assuming a standard adult BW of 70 kg, as commonly adopted in the literature ([Esposito et al., 2019](#)), and RfD (Reference Dose for Oral Exposure, mg kg⁻¹ BW day⁻¹) represents an estimate of the daily human exposure to a toxic element that is likely to be without appreciable health risk over a lifetime according to the [US Environmental Protection Agency \(EPA\) \(2023\)](#). The EDI was calculated as described in [Section 2.3](#), where C represents the concentration of the potentially hazardous chemical.

The potential health risk for Al was evaluated based on the tolerable weekly intake (TWI; kg⁻¹ BW week⁻¹), according to the [European Food Safety Authority \(EFSA\) \(2008\)](#). Lead content was compared with the maximum level permitted for this element in leafy vegetables under [Regulation \(EU\) 2023/915](#).

For nitrate, the ADI (3.7 mg kg⁻¹ BW day⁻¹) established by [EFSA \(2017\)](#) was used in place of the RfD for HRI calculation.

2.5. Statistical analysis

Each of the 18 tanks constituted the experimental unit. Values obtained from three plantlets sampled per tank for growth parameters were averaged before statistical analysis.

All statistical analyses were performed using the R statistical environment ([R Core Team, 2024](#); version ≥ 4.1.0). Descriptive statistics are presented as mean ± standard deviation (SD). Prior to inferential testing, the assumptions of the parametric model were assessed for every response variable. Normality was evaluated using the Shapiro–Wilk test applied to the within-group residuals—the quantity required to be normally distributed under the ANOVA model—and homogeneity of variances was assessed using the Brown–Forsythe test (Levene's test centred on the median), which is robust to departures from normality. Because most variables violated at least one of these assumptions (Supplementary Tables S1–S3), a uniform non-parametric framework was adopted throughout the study to ensure consistency of the statistical analyses across variables reported in the same tables. Accordingly, non-parametric tests were applied to all growth, morphological, and

chemical variables.

Morphological parameters and yield were analyzed separately for each developmental stage (microgreens and baby leaves). Within each stage, comparisons between full-strength (H) and half-strength (H/2) Hoagland nutrient solutions were performed using the Wilcoxon rank-sum test (unpaired). For chemical parameters, all four experimental combinations (microgreens H, microgreens H/2, baby leaves H, baby leaves H/2) were compared simultaneously using pairwise Wilcoxon rank-sum tests. P-values were adjusted for multiple comparisons using Holm's correction method. Compact Letter Displays (CLD) were used to summarize significant pairwise differences.

Principal Component Analysis (PCA) was conducted for chemical traits on scaled datasets to explore multivariate patterns. Wild samples were excluded from inferential statistical comparisons because they were not part of the experimental design and therefore differed from cultivated plants in several uncontrolled factors (e.g., growing environment, plant age, and genetic background). However, they were included in descriptive analyses and PCA as an external benchmark, since PCA was used as an exploratory tool to provide a reference for the natural chemical profile of the species rather than to test treatment effects. PCA results were visualized using the factoextra package (Kassambara and Mundt, 2020), with 80% confidence ellipses.

3. Results

3.1. Growth parameters and yield

Nutrient solution concentration did not affect growth parameters or yield in either microgreens or baby leaves (Tables S4 and S5). At the microgreen stage, plantlets recorded an average FW of 63 mg, a DW of 5.25 mg, and a LA of 1.3 cm², with a DW% of 8.4. Baby leaf plants reached an average FW of 2.0 g, a DW of 0.2 g, and a LA of 80.09 cm², developing approximately 9.5 leaves with an average length of 14.85 cm. The DW% for baby leaves was 9.3. Overall yields were 0.58 kg m⁻² for microgreens and 1.31 kg m⁻² for baby leaves.

3.2. Chemical characterization

3.2.1. Chlorophylls, carotenoids, and antioxidants

As reported in Table 1, chlorophyll concentration was significantly higher in baby leaves than in microgreens. Baby leaf plants did not show differences due to the nutrient solution, with an average total chlorophyll content of about 1560 mg kg⁻¹ FW across the two nutrient levels. On the contrary, chlorophyll concentration in microgreens was lower under the H/2 treatment (853.71 vs. 1009.61 mg kg⁻¹ FW). Carotenoids reached the highest concentration in baby leaf H (180.09 mg kg⁻¹ FW), with significant difference as compared to microgreens H/2 (Table 1). For total phenols, flavonoids and FRAP higher values were observed in baby leaf plants grown in H/2 nutrient solution compared to microgreens and baby leaves under the H treatment (Table 1). The chlorophyll and carotenoid composition of the plants grown hydroponically was consistent with that of the wild reference plants, which in contrast were

characterized by higher levels of total phenols (541.88 mg kg⁻¹ FW) and flavonoids (1399.54 mg kg⁻¹ FW).

3.2.2. Protein content

As shown in Fig. 1, the concentration of the nutrient solution did not affect the protein content of either baby leaf plants or microgreens. However, baby leaf plants grown under the H/2 solution exhibited a significantly higher protein concentration (2.52 g 100 g⁻¹ FW) compared to microgreens (1.60–1.90 g 100 g⁻¹ FW for H and H/2, respectively), and were similar to the wild reference plants (2.76 g 100 g⁻¹ FW).

3.2.3. Soluble sugar concentrations

Baby leaf plants grown under the H/2 solution showed a slightly but significantly higher concentration in soluble sugars (1.96 g kg⁻¹ FW) than the other cultivated plants (1.45, 1.60 and 1.62 g kg⁻¹ FW for microgreens H, microgreens H/2 and baby leaf H, respectively). Sugar content in wild plants was markedly higher (13.66 g kg⁻¹ FW) (Fig. 2).

3.2.4. Vitamin content

The vitamin profile of cultivated *H. radiata* plants exhibited distinct patterns across growth stages and nutrient solution concentrations (Table 2). Vitamin B5 was below LOD and was therefore not included in the table. Baby leaves accumulated higher vitamin C levels than microgreens, with no significant differences between nutrient regimes (approximately 15.5 mg kg⁻¹ FW on average), whereas microgreens showed lower concentrations under the H treatment. A similar trend was observed for vitamin B1. In contrast, vitamin A was influenced by the nutrient solution in baby leaves, reaching the highest value under the H treatment, which was also significantly greater than that recorded in microgreens grown under H/2. Vitamin B2 peaked in baby leaves grown under H/2, while the other treatments did not differ. Conversely, vitamin B3 was higher in microgreens than in baby leaves, with significant differences between nutrient solutions at both growth stages. Vitamin B6 also showed a growth-stage effect, but with an opposite trend, peaking in baby leaves under H/2. Finally, vitamin B9 concentration was lower in microgreens grown under H/2 compared to those grown under H and to baby leaves under H/2. Despite these differences, the vitamin contents of cultivated plants were overall comparable to those measured in wild reference samples (Table 2).

3.2.5. Major minerals and trace elements

The statistical analysis revealed differences in the content of major minerals among the four stage × nutrient solution combinations; however, all values were within the same order of magnitude (Table 3). Average concentrations (mg kg⁻¹ FW) were approximately 900 for Ca, 530 for P, 470 for Mg, 517 for Na, and 2500 for K. Calcium, Mg, and K exhibited similar patterns across growth stages and nutrient solutions, with significantly higher concentrations in microgreens grown in half-strength solution compared to those grown in full-strength solution. Baby leaves showed intermediate values, irrespective of the nutrient solution. Microgreens cultivated in H/2 also displayed higher P concentrations than all other treatments. In contrast, Na reached its highest

Table 1

Concentrations of chlorophylls (Chl a, Chl b, and total), carotenoids, total phenols, flavonoids, and antioxidant activity (measured by the FRAP assay) in *Hyoscyamus radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark.

Treatment	Chl a (mg kg ⁻¹ FW)	Chl b (mg kg ⁻¹ FW)	Chl a+b (mg kg ⁻¹ FW)	Carotenoids (mg kg ⁻¹ FW)	Phenols (mg kg ⁻¹ FW)	Flavonoids (mg kg ⁻¹ FW)	FRAP (mmol kg ⁻¹ FW)
Microgreens H	740.80 ± 136.02 b	246.21 ± 52.30 b	1009.61 ± 192.49 b	159.62 ± 18.84 ab	66.76 ± 0.98 d	267.46 ± 39.31 b	68.0 ± 18.65 c
Microgreens H/2	626.37 ± 33.29 c	208.22 ± 13.77 c	853.71 ± 45.44 c	142.65 ± 8.01 b	70.40 ± 6.91 c	256.59 ± 10.23 b	47.41 ± 22.73 d
Baby leaf H	1081.50 ± 167.39 a	422.63 ± 102.56 a	1537.64 ± 274.67 a	180.09 ± 20.26 a	78.60 ± 10.47 b	291.30 ± 78.26 b	85.53 ± 6.34 b
Baby leaf H/2	1081.28 ± 120.53 a	470.73 ± 105.38 a	1585.31 ± 217.82 a	161.41 ± 25.40 ab	88.79 ± 12.39 a	343.34 ± 16.75 a	109.99 ± 14.57 a
Wild reference plants	907.88 ± 108.38	341.43 ± 63.81	1256.61 ± 183.00	200.94 ± 15.87	541.88 ± 78.90	1399.54 ± 232.06	228.05 ± 51.08

Data are presented as mean ± standard deviation (SD) (n = 18 replicates per treatment). Mean values within columns followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

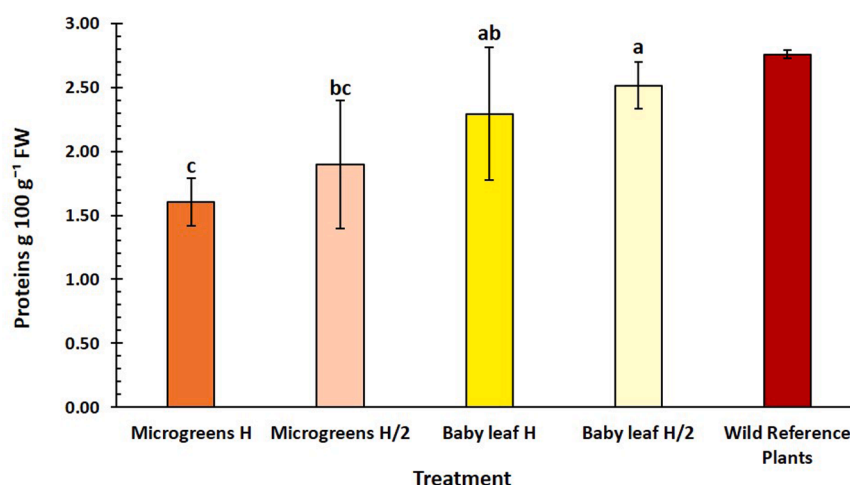


Fig. 1. Protein content in *Hyosieris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild reference plants were included as an external benchmark. Data are presented as mean $\pm$ standard deviation (SD) ($n = 18$ replicates per treatment). Different letters show significant differences according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

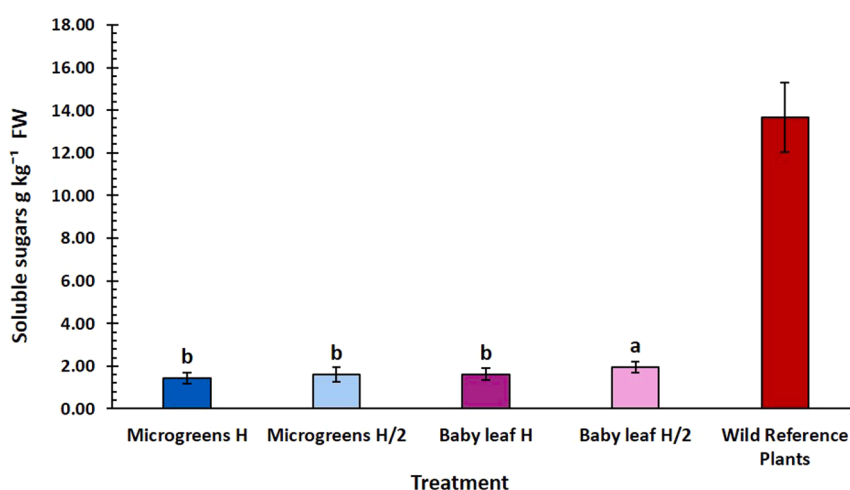


Fig. 2. Soluble sugar content in *Hyosieris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark. Data are presented as mean $\pm$ standard deviation (SD) ($n = 18$ replicates per treatment). Different letters show significant differences according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

Table 2

Vitamin content (C, A, B1, B2, B3, B6, and B9) in *Hyosieris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark.

Treatment	Vit C (mg kg ⁻¹ FW)	Vit A (mg RAE kg ⁻¹ FW)	Vit B1 (mg kg ⁻¹ FW)	Vit B2 (mg kg ⁻¹ FW)	Vit B3 (mg kg ⁻¹ FW)	Vit B6 (mg kg ⁻¹ FW)	Vit B9 (mg kg ⁻¹ FW)
Microgreens H	11.52 $\pm$ 0.95 c	6.65 $\pm$ 0.78 ab	0.41 $\pm$ 0.09 c	0.64 $\pm$ 0.06 b	4.81 $\pm$ 0.09 a	0.20 $\pm$ 0.001 c	0.50 $\pm$ 0.09 a
Microgreens H/2	12.39 $\pm$ 0.84 b	5.94 $\pm$ 0.33 bc	0.59 $\pm$ 0.10 b	0.61 $\pm$ 0.05 b	4.37 $\pm$ 0.20 b	0.19 $\pm$ 0.001 d	0.39 $\pm$ 0.05 b
Baby leaf H	15.96 $\pm$ 1.92 a	7.50 $\pm$ 0.84 a	1.11 $\pm$ 0.35 a	0.58 $\pm$ 0.13 b	3.67 $\pm$ 0.92 c	1.33 $\pm$ 0.77 b	0.46 $\pm$ 0.04 ab
Baby leaf H/2	15.09 $\pm$ 5.08 a	5.90 $\pm$ 1.86 c	1.06 $\pm$ 0.25 a	0.84 $\pm$ 0.31 a	2.78 $\pm$ 1.07 d	1.95 $\pm$ 0.76 a	0.47 $\pm$ 0.11 a
Wild reference plants	11.34 $\pm$ 2.35	8.37 $\pm$ 0.66	0.69 $\pm$ 0.04	0.74 $\pm$ 0.14	1.96 $\pm$ 0.22	0.20 $\pm$ 0.001	0.49 $\pm$ 0.17

Data are presented as mean $\pm$ standard deviation (SD) ($n = 18$ replicates per treatment). Mean values within columns followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

concentration in baby leaf grown under H/2.

Wild reference plants showed Ca and K levels comparable to those of cultivated plants, but were characterized by higher P and lower Mg contents, and particularly low Na concentrations (90 mg kg⁻¹ FW).

The content of essential trace elements is reported in Table 4, with the exception of Se, which was below LOD. Iron concentrations were higher in baby leaves and lower in microgreens grown under the H treatment. Microgreens accumulated greater amounts of Mn, Cu, and

Mo. Differences between nutrient solutions were detected for Mn and Mo at both growth stages, whereas Fe and Cu were affected by the nutrient solution only in microgreens. No significant differences related to growth stage or nutrient solution were observed for Zn. Essential trace elements were more abundant in the wild than in cultivated plants, except for Mo and Cu.

Table 3

Concentrations of major minerals (Ca, K, Mg, Na, and P) in *Hyoseris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark.

Treatment	Ca (mg kg ⁻¹ FW)	K (mg kg ⁻¹ FW)	Mg (mg kg ⁻¹ FW)	Na (mg kg ⁻¹ FW)	P (mg kg ⁻¹ FW)
Microgreens H	818.79 ± 139.52 b	2201.13 ± 382.89 b	400.89 ± 91.97 b	490.07 ± 103.90 b	520.81 ± 12.09 b
Microgreens H/2	962.63 ± 59.29 a	2639.17 ± 126.46 a	499.65 ± 61.99 a	510.87 ± 23.98 b	578.17 ± 15.33 a
Baby leaf H	920.77 ± 73.14 ab	2619.65 ± 163.51 a	459.77 ± 58.98 ab	500.03 ± 19.85 b	516.37 ± 14.64 b
Baby leaf H/2	924.29 ± 69.21 ab	2492.44 ± 193.07 ab	470.87 ± 59.09 ab	566.66 ± 40.58 a	523.51 ± 25.06 b
Wild reference plants	870.89 ± 21.24	2236.86 ± 314.01	292.95 ± 24.39	90.03 ± 13.59	992.14 ± 231.20

Data are presented as mean ± standard deviation (SD) (n = 18 replicates per treatment). Mean values within columns followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

Table 4

Concentrations of essential trace elements (Cu, Fe, Mn, Mo, and Zn) in *Hyoseris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark.

Treatment	Cu (mg kg ⁻¹ FW)	Fe (mg kg ⁻¹ FW)	Mn (mg kg ⁻¹ FW)	Mo (mg kg ⁻¹ FW)	Zn (mg kg ⁻¹ FW)
Microgreens H	6.36 ± 0.91 b	29.72 ± 2.79 b	6.39 ± 0.52 b	0.67 ± 0.04 b	1.40 ± 0.06 a
Microgreens H/2	7.33 ± 1.05 a	40.88 ± 10.65 a	7.01 ± 0.10 a	0.68 ± 0.05 a	1.36 ± 0.14 a
Baby leaf H	1.57 ± 1.26 c	63.51 ± 31.79 a	3.02 ± 0.56 c	0.49 ± 0.10 d	1.56 ± 0.33 a
Baby leaf H/2	0.94 ± 0.12 c	58.76 ± 28.88 a	2.59 ± 0.19 d	0.59 ± 0.04 c	1.39 ± 0.07 a
Wild reference plants	6.47 ± 3.74	130.00 ± 25.79	9.39 ± 1.75	0.67 ± 0.07	9.84 ± 2.03

Data are presented as mean ± standard deviation (SD) (n = 18 replicates per treatment). Mean values within columns followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

3.2.6. Non-essential trace elements and nitrate

In cultivated plants, non-essential trace elements were generally detected at low concentrations, although both growth stage and nutrient solution strength significantly affected their accumulation (Table 5). Aluminum was the most abundant element, with higher levels in H microgreens than in H/2, whereas baby leaves showed intermediate values with no significant differences between nutrient regimes. Chromium content in baby leaves was one order of magnitude greater than in microgreens, and it was also influenced by nutrient strength being higher under the H solution than under H/2. Nickel and Pb exhibited a similar pattern, with significantly lower accumulation in H microgreens and no differences among the other growth stage × nutrient solution combinations. Arsenic responded differently to nutrient regime, but in opposite ways: it was lower in H than in H/2 in microgreens, and higher in H than in H/2 in baby leaves. Baby leaf plants accumulated more Cd than microgreens. Differences in Sb were observed only under the H/2 solution, with higher values in baby leaves.

Wild plants showed much higher concentrations of Cr, Ni, and Cd than cultivated plants, while Pb levels in wild samples were below the LOD. Cultivated plants accumulated significantly more nitrate than wild reference samples, which showed negligible nitrate content (Table 6). Microgreens cultivated under both H and H/2, together with baby leaves grown under H, exhibited no statistically significant differences in nitrate levels. By contrast, baby leaves grown in H/2 showed significantly lower nitrate levels than all other cultivated treatments (Table 6).

Table 5

Concentrations of non-essential trace elements (Al, As, Cd, Cr, Ni, Pb, and Sb) in *Hyoseris radiata* microgreens and baby leaves grown under full-strength (H) or half-strength (H/2) Hoagland nutrient solution in a floating hydroponic system. Wild plants were included as an external benchmark.

Treatment	Al (mg kg ⁻¹ FW)	As (μg kg ⁻¹ FW)	Cd (μg kg ⁻¹ FW)	Cr (μg kg ⁻¹ FW)	Ni (μg kg ⁻¹ FW)	Pb (μg kg ⁻¹ FW)	Sb (μg kg ⁻¹ FW)
Microgreens H	33.02 ± 4.69 a	5.12 ± 1.27 b	0.84 ± 0.62 b	40.24 ± 3.98 c	42.69 ± 6.09 b	21.60 ± 3.15 b	3.31 ± 1.69 b
Microgreens H/2	25.74 ± 6.61 b	8.17 ± 1.27 a	1.05 ± 0.69 b	63.00 ± 16.05 d	97.82 ± 30.65 a	38.17 ± 15.90 a	6.93 ± 1.78 a
Baby leaf H	32.66 ± 16.09 ab	9.28 ± 6.12 a	2.36 ± 1.18 a	367.48 ± 223.82 a	106.71 ± 38.25 a	35.92 ± 9.68 a	4.92 ± 2.99 ab
Baby leaf H/2	30.40 ± 16.83 ab	5.32 ± 1.41 b	3.20 ± 1.32 a	200.45 ± 91.31 b	123.29 ± 50.99 a	37.31 ± 8.73 a	2.65 ± 0.85 b
Wild reference plants	47.43 ± 3.99	9.75 ± 0.97	100.15 ± 0.94	837.50 ± 519.55	6786.03 ± 865.05	<LOD	10.34 ± 0.85

Data are presented as mean ± standard deviation (SD) (n = 18 replicates per treatment). Mean values within columns followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

Table 6

Nitrate content in *Hyoseris radiata* harvested at the microgreen or baby-leaf stage and grown under two Hoagland solution concentrations (full strength, H, and half-strength, H/2). Wild reference plants were included as an external benchmark.

Treatment	Nitrate (mg kg ⁻¹)
Microgreens H	7079.26 ± 1434.36 a
Microgreens H/2	6803.04 ± 948.74 a
Baby leaf H	6644.28 ± 334.94 a
Baby leaf H/2	4286.69 ± 1186.06 b
Wild reference plants	18.51 ± 0.61

Data are presented as mean ± standard deviation (SD) (n = 18 replicates per treatment). Mean values followed by different letters are significantly different according to the non-parametric Wilcoxon rank-sum test with Holm's adjustment ($p \leq 0.05$).

3.3. Contribution to nutrient dietary intake

Vitamin A provided the highest EDI%, followed by vitamin B9 (Table 7). On the contrary, the lowest EDI% values were recorded for vitamin C (Table 7). Regarding essential elements, *H. radiata* could contribute to dietary intake particularly of Mo, followed by Fe in baby leaf product or Cu in microgreens. Sodium and Zn exhibited the lowest EDI% values (Table 7). In all cases, the contribution provided by baby leaves was greater than that of microgreens.

Table 7

Estimated dietary intake of vitamins and minerals expressed as percentage (EDI %) of the Population Reference Intake (PRI), Adequate Intake (AI), or Suggested Dietary Target (SDT) for adults aged 18–24, based on the consumption of 20 g (microgreens) or 50 g (baby leaves) of *Hyoseris radiata*. When PRI, AI, or SDT values differed between males and females, EDI% was calculated using male reference values.

Nutrient	PRI/AI/SDT mg day ⁻¹		EDI%	
	Men	Women	Microgreens	Baby leaf
Vit A	0.75	0.65	16.79	44.67
Vit C	105	85	0.23	0.74
Vit B2	1.6	1.6	0.78	2.22
Vit B3	18	18	0.51	0.90
Vit B6	1.6	1.4	0.24	5.13
Vit B9	0.33	0.33	2.70	7.05
Ca	950	950	1.81	4.86
K	4500	4500	1.08	2.84
Mg	350	350	2.57	6.65
Na	1500	1500	0.67	1.78
P	550	550	2.00	4.73
Cu	1.4	1.3	9.79	4.50
Fe	10	18	7.06	30.57
Mn	2.5	2.3	5.36	5.61
Mo	0.065	0.065	20.77	41.54
Zn	12	9	0.23	0.61

3.4. Health risk assessment

The results of the health risk assessment for cultivated plants are reported in Table 8. The EDI_{BW} values calculated for non-essential trace elements were very low, resulting in HRIs well below 1 for both microgreens and baby leaves. Similarly, the estimated weekly intake of AI was below the TWI. In contrast, a potential health risk associated with nitrate consumption was identified for baby leaf (HRI > 1). Lead content ranged from 21.6 to 38.2 µg kg⁻¹ (Table 5), values far below the maximum level permitted for this element in leafy vegetables (0.3 mg kg⁻¹, Reg. UE 2023/915).

Table 8

Estimated daily intake per kg of body weight (EDI_{BW}, mg kg⁻¹ body weight day⁻¹) and Health Risk Index (HRI) for selected toxic elements and nitrate, based on the consumption of 20 g (microgreens) or 50 g (baby leaves) of *Hyoseris radiata*. RfD = oral reference dose (mg kg⁻¹ body weight day⁻¹) (US EPA, 2023). ADI = acceptable daily intake (mg kg⁻¹ body weight day⁻¹) (EFSA, 2017). For AI (RfD not available), TWI (tolerable weekly intake, mg kg⁻¹ body weight week⁻¹) (EFSA, 2008) was used to calculate the estimated weekly intake (EWI, mg kg⁻¹ body weight week⁻¹).

Chemical		Microgreens	Baby leaf
As (RfD = 6 × 10 ⁻⁵)	EDI _{BW}	1.90 × 10 ⁻⁶	5.22 × 10 ⁻⁶
	HRI	3.16 × 10 ⁻²	8.69 × 10 ⁻²
Cd (RfD = 1 × 10 ⁻³)	EDI _{BW}	2.69 × 10 ⁻⁷	1.99 × 10 ⁻⁶
	HRI	2.69 × 10 ⁻⁴	1.99 × 10 ⁻³
Cr (RfD = 9 × 10 ⁻⁴)	EDI _{BW}	1.47 × 10 ⁻⁵	2.03 × 10 ⁻⁴
	HRI	1.64 × 10 ⁻²	2.25 × 10 ⁻¹
Mn (RfD = 1.4 × 10 ⁻¹)	EDI _{BW}	1.91 × 10 ⁻³	2.00 × 10 ⁻³
	HRI	1.37 × 10 ⁻²	1.43 × 10 ⁻²
Mo (RfD = 5 × 10 ⁻³)	EDI _{BW}	1.93 × 10 ⁻⁴	3.86 × 10 ⁻⁴
	HRI	3.86 × 10 ⁻²	7.71 × 10 ⁻²
Ni (RfD = 2 × 10 ⁻²)	EDI _{BW}	2.01 × 10 ⁻⁵	8.21 × 10 ⁻⁵
	HRI	1.00 × 10 ⁻³	4.11 × 10 ⁻³
Sb (RfD = 4 × 10 ⁻⁴)	EDI _{BW}	1.46 × 10 ⁻⁶	2.70 × 10 ⁻⁶
	HRI	3.66 × 10 ⁻³	6.76 × 10 ⁻³
Zn (RfD = 3 × 10 ⁻¹)	EDI _{BW}	3.94 × 10 ⁻⁴	1.05 × 10 ⁻³
	HRI	1.31 × 10 ⁻³	3.51 × 10 ⁻³
NO ₃ (ADI = 3.7)	EDI _{BW}	1.98	3.90
	HRI	5.35 × 10 ⁻¹	1.05
AI (TWI = 1)	EWI	5.88 × 10 ⁻²	1.57 × 10 ⁻¹

3.5. Principal component analysis of chemical parameters

Principal Component Analysis (PCA) was performed on scaled chemical variables, including pigments, phenolic compounds, antioxidant capacity, vitamins, major minerals, trace elements, and nitrate concentrations (Fig. 3). Wild reference plants were included as an external group.

The first two principal components explained 61.6% of the total variance (PC1: 42.8%; PC2: 18.8%). PC1 clearly separated wild plants from hydroponically grown samples. This separation was primarily associated with markedly higher phenols, flavonoids, and iron concentrations in wild plants, together with higher soluble sugars and trace element concentrations, and lower nitrate levels compared with cultivated plants. PC2 mainly discriminated between developmental stages. Baby leaves were characterized by higher chlorophyll, vitamin B6, antioxidant capacity, and iron, whereas microgreens were positioned toward higher nitrate levels and lower pigment accumulation. Within each developmental stage, H and H/2 treatments partially overlapped, suggesting that nutrient solution strength contributed less to overall chemical variability than growth stage. Variable loadings and contributions to PC1, PC2, and PC3 are reported in Supplementary Tables S6.

4. Discussion

The growing interest in WEPs as sources of nutritious and sustainable foods has stimulated research on their introduction into cultivation systems. To our knowledge, the present study provides the first assessment of *Hyoseris radiata* grown hydroponically, evaluating growth performance, yield, nutritional and nutraceutical characteristics, and safety-related parameters, of microgreens and baby leaves under two different nutrient solution concentrations. Among leafy WEPs, only a few species have been investigated for microgreens and baby leaf production (Lenzi et al., 2019; Baldi et al., 2023).

4.1. Growth performance and yield response

H. radiata showed stable growth parameters and yield across nutrient solution strengths at both the microgreen and baby leaf stages (Tables S4 and S5). During early developmental stages seedlings rely largely on seed reserves (Fenner and Thompson, 2005); however, several studies have demonstrated that the use of nutrient solutions in place of water alone enhances the growth performance of microgreens (Wieth et al., 2019; El-Nakhel et al., 2021; Keutgen et al., 2021). In the literature, most of the nutrient solutions for microgreens are based on the Hoagland solution composition, often used at reduced concentrations (50% or lower) (Keutgen et al., 2021). Nevertheless, full strength nutrient solutions may result in higher yields in some species (Wieth et al., 2019). In the present study, however, microgreens production did not benefit from full-strength nutrient supply. Similar findings were reported by Fayeizadeh et al., 2023 in basil microgreens. As for baby leaf crops, they are typically produced under higher nutrient levels than microgreens, with nitrogen concentrations in nutrient solutions generally ranging from 8 to 12 mmol L⁻¹ and reaching up to 15 mmol L⁻¹ under standard cultivation conditions to support high yield (Nicola et al., 2015; Voutsinos-Frantzis et al., 2024). However, it should be considered that many wild plants, particularly those growing in ruderal habitats, exhibit specific adaptations in mineral balance and nutrient acquisition that enable them to survive in nutrient-poor ecosystems (Aerts and Chapin III, 1999). This adaptive capacity to cope with nutrient-limited conditions may result in reduced fertilizer requirements during cultivation, offering both economic and environmental benefits. Consistently, in the present study, the full-strength nutrient solution did not enhance the growth performance of *H. radiata* baby leaves. A similar response was observed in a cultivation trial with the WEP *Cichorium spinosum* L., where plant growth was maintained despite a reduction in total nitrogen concentration from 16 to 4 mmol L⁻¹ (Chatzigianni et al.,

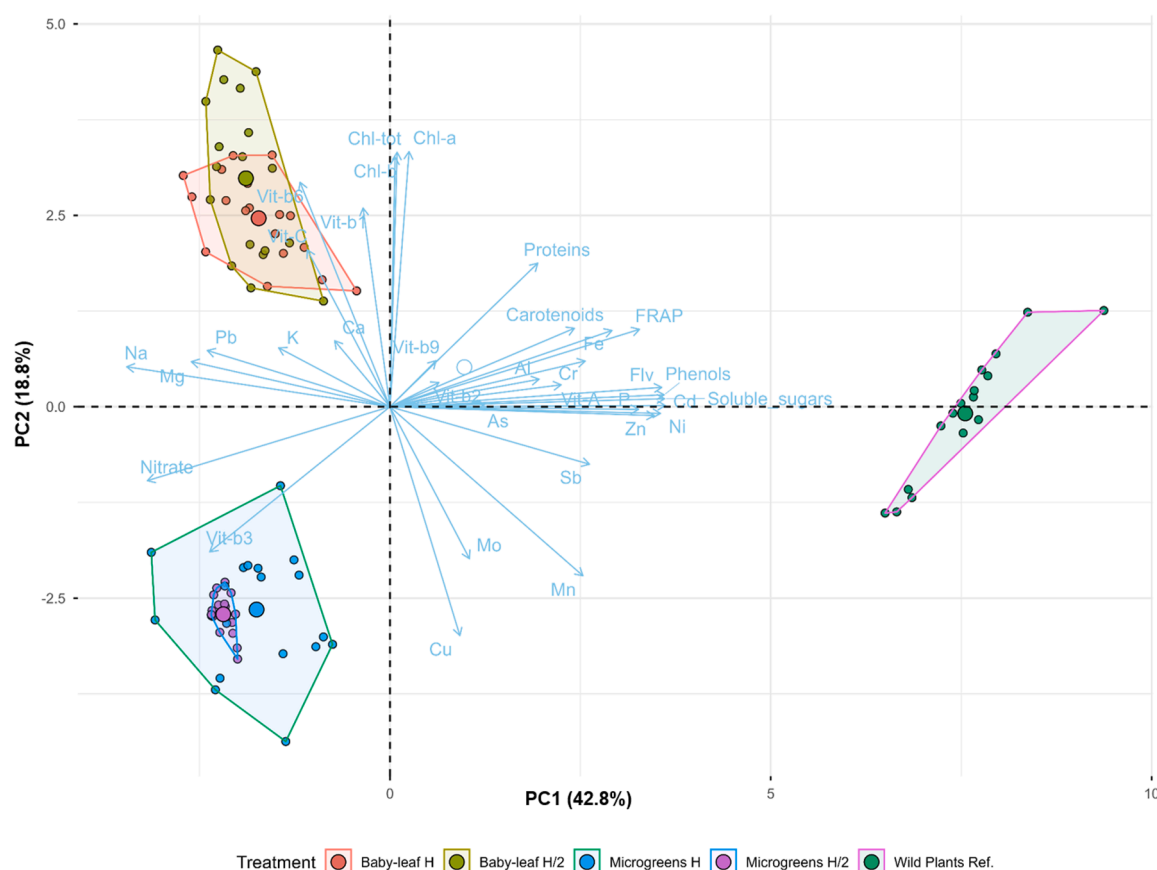


Fig. 3. Principal Component Analysis (PCA) of chemical composition parameters of baby leaf and microgreens of *Hyoseris radiata* grown under two Hoagland solution concentrations (full strength, H, and half-strength, H/2). Wild reference plants were included for comparison.

2018). Collectively, these results indicate that *H. radiata* has relatively modest nutrient requirements during cultivation, making it a promising candidate for low-input hydroponic production systems.

In our study, averaged across the two nutrient solutions, yield reached approximately 0.6 and 1.3 kg FW m⁻² for microgreens and baby leaves, respectively. These values exceeded the fresh biomass reported for *H. radiata* cultivated in a peat-perlite substrate enriched with a controlled-release fertilizer and harvested 30 days after sowing (approximately 0.45 kg FW m⁻²; Benvenuti et al., 2017). However, yields were lower than those reported for several microgreen crop species (Paradiso et al., 2018; Renna et al., 2018; Bulgari et al., 2017), lettuce baby leaf grown in floating systems (Conversa et al., 2021a; b), and microgreens and/or baby leaves of other WEPs cultivated under conditions similar to those of the present study (Lenzi et al., 2019; Baldi et al., 2023).

4.2. Chemical composition

Many WEPs are recognized as valuable sources of essential minerals, vitamins, and antioxidant secondary metabolites (García-Herrera et al., 2016; Tardío et al., 2016; Pinela et al., 2017). However, data reported in the literature indicate that WEPs nutritional and nutraceutical composition is highly variable even within the same species, with differences driven by genetic factors, environmental conditions, and harvesting season. The intraspecific variation in the qualitative and quantitative composition of metabolites in wild plants often reflects their adaptive capacity to challenging environmental conditions (Accogli et al., 2024). Variability among ecotypes, growing sites, and sampling periods in terms of phenolic compounds, antioxidant capacity, and mineral composition have been widely reported for several species, including

Cichorium spinosum L., *Portulaca oleracea* L., and *Taraxacum campyloides* G. E. Haglund (Petropoulos et al., 2016, 2019; Kromberga et al., 2023). Moreover, cultivation practices can significantly affect the chemical composition of plants compared with their wild-harvested counterparts. Studies on leafy WEPs have reported both increases and decreases in nutritional quality under cultivation conditions (Bosha et al., 2016; Botella et al., 2024), with outcomes strongly influenced by the production system adopted, including soil-based and soilless cultivation systems (Ceccanti et al., 2020; 2021), as well as by the developmental stage at harvest, such as the microgreen or baby leaf stage (Lenzi et al., 2019). Plant developmental stage is particularly relevant because substantial changes in the concentration and distribution of metabolites, vitamins, antioxidants, and other bioactive compounds occur during growth (Di Gioia et al., 2017; El-Nakhel et al., 2021). Therefore, the harvest stage may be considered a key factor for modulating and optimizing the nutritional profile of plant-derived foods through targeted agronomic strategies.

The chlorophyll and carotenoid contents detected in *H. radiata* (Table 1) were consistent with values previously reported for microgreens and baby leaf plants of *Sanguisorba minor* L., *Sinapis arvensis* L., and *Taraxacum officinale* (Weber) ex Wiggers (Lenzi et al., 2019). Carotenoid concentrations in *H. radiata* were also comparable to those described by Cámara et al., 2016 for several Mediterranean WEPs. Baby leaves showed higher chlorophyll levels than microgreens, likely reflecting the progressive development of the photosynthetic apparatus and greater leaf expansion, both of which enhance light-harvesting capacity (Dantas et al., 2024). Consistent with previous studies (Vastakaitė-Kairienė et al., 2020; Di Bella et al., 2020; El-Nakhel et al., 2021; Mallor et al., 2023), the baby leaf stage also exhibited higher total phenolic and flavonoid contents than the microgreen stage

(Table 1). This trend may be associated with the gradual activation of secondary metabolism during plant development and with prolonged exposure to environmental factors that stimulate phenylpropanoid biosynthesis (Di Bella et al., 2020; El-Nakhel et al., 2021). Moreover, the transition from partial reliance on seed reserves in microgreens to a fully autotrophic metabolism in baby leaves may further enhance the synthesis of carbon-based secondary metabolites, in accordance with the carbon/nutrient balance theory (Caretto et al., 2015). Wild reference samples contained higher concentrations of these compounds than the cultivated plants analyzed in this study. Their values were of the same order of magnitude, although slightly lower, than those reported by Vitiello et al., 2024 for the same species, also collected in the wild. Differences in genotype, environmental growing conditions, and extraction or quantification methods may explain the variability between the two studies. The higher antioxidant content observed in wild plants compared with cultivated ones may reflect exposure to natural environmental stressors and the consequent need to counteract oxidative damage (Uarrotta et al., 2018). As expected, FRAP values followed the same pattern as total phenolic content, with baby leaves showing significantly higher values than microgreens and wild plants exhibiting higher values than cultivated plants (Table 1). The FRAP values measured in cultivated plants were comparable to those reported for cultivated *H. radiata* by Benvenuti et al., 2017.

Vegetables are not considered a primary source of protein because they provide relatively low amounts compared to other foods, such as legumes among plant-based foods (Maphosa et al., 2017). In the present study, protein concentrations ranged from 1.60 g 100 g⁻¹ FW (microgreens grown in H nutrient solution) to 2.76 g 100 g⁻¹ (wild reference plants). These values are consistent both to those measured in microgreens and baby leaves of crop species (Ghoora et al., 2020; Collado-González et al., 2022), as well as those reported for different WEPs (Tardío et al., 2016). *H. radiata* protein content showed an increasing trend with the advancing growth stage and decreasing nutrient level. The interpretation of this trend is not straightforward, and the available literature on the subject remains inconsistent. For example, in amaranth, Ayeñi (2021) reported significant differences in protein content between microgreens/baby leaves and mature field-grown plants, with mature leaves containing lower protein levels than microgreens. In contrast, Ebert et al., 2014 found that protein content was highest in fully developed leafy amaranth, intermediate in sprouts, and lowest in microgreens, which also exhibited the lowest dry matter content. Substantial differences in soluble sugar content were observed between cultivated and wild plants in the present study (Fig. 2). The higher sugar concentrations detected in wild populations may represent an adaptive response that helps plants cope with stress factors such as drought, nutrient limitation, and unfavorable soil conditions. Under these conditions, wild plants tend to accumulate soluble sugars in order to maintain osmotic homeostasis and preserve cellular integrity (Yamada and Osakabe, 2018). The soluble sugar contents observed were in close agreement with those reported by Tardío et al., 2016 for other WEPs. For instance, in *Taraxacum officinale*, soluble sugar contents ranged from 1.27 to 1.46 g 100 g⁻¹ FW.

To our knowledge, no data on the vitamin and elemental composition of *H. radiata* have been published to date. According to Regulation (EU) 1169/2011, foods may be considered significant sources of vitamins and mineral elements if they provide at least 15% of the nutrient reference values (NRVs) set out in Annex XIII. Cultivated *H. radiata* exhibited some significant differences in vitamin contents related to growth stage and nutrient solution concentration; however, both microgreens and baby leaves, whether grown in full- or half-strength nutrient solution, exceeded these thresholds for vitamin A (threshold: 1.2 mg kg⁻¹) and vitamin B9 (0.3 mg kg⁻¹) (Table 2). Accordingly, the EDI% values were highest for these two vitamins. The EDI% of vitamin A was 16.79% for microgreens and 44.67% for baby leaves, whereas for vitamin B9 the two products provided an EDI% of 2.70% and 7.05%, respectively. The higher values for baby leaves were due to the larger

estimated portion (50 g) compared to microgreens (20 g). The microgreens portion size reflects their typical use as salad enhancers or dish garnishes rather than as a main course (Pinto et al., 2015). Vitamin A concentrations in cultivated *H. radiata* were similar to that of the wild reference plants, as well as those reported for other *Asteraceae* WEPs (Orlandi et al., 2024). Regarding crop species, different accessions of baby leaf lettuce showed an average β -carotene (pro-vitamin A) content of 49 mg kg⁻¹ (Simko, 2019), whereas β -carotene concentrations among 25 commercially grown microgreens ranged from 6 to 121 mg kg⁻¹ (Xiao et al., 2012). It is recognised that the most important contribution of wild edible foods to vitamin B complex in the human diet is due to their content in vitamin B9 (Sánchez-Mata et al., 2016). Nevertheless, there are very few studies on the content of this vitamin in wild leafy vegetables. According to data reported in the review by Sánchez-Mata et al., 2016 on Mediterranean wild vegetables, *Rumex pulcher* L. shows the highest vitamin B9 content, reaching around 5 mg kg⁻¹. This concentration is approximately one order of magnitude higher compared to *H. radiata*, both cultivated and wild-collected (Table 2). In contrast, vitamin B9 in *H. radiata* was comparable to levels found in crop species, such as baby leaf lettuce (Kim et al., 2018) and *Brassica rapa* L. subsp. *chinensis* (L.) Hanelt microgreens (Zou et al., 2021).

The contents in major minerals of *H. radiata* microgreens and baby leaves, as well as of wild reference plants, did not reach the 15% NRV threshold (Table 3). Conversely, many are the leafy WEPs that have been reported as good sources of Ca, K, and Mg according to Regulation (EU) 1169/2011 (Sánchez-Mata et al., 2016). The leaves of some species of *Parietaria* may even contain over 8 g kg⁻¹ Ca, while different *Chenopodium* species are notable for their K content (*C. album*; approximately 10 g kg⁻¹) and Mg content (*C. murale* (L.) S.Fuentes, Uotila & Borsch and *C. opulifolium* Schrad. ex W.D.J.Koch & Ziz; both around 4 g kg⁻¹). The P concentrations of *H. radiata* fell within the range normally observed for leafy vegetables (200–700 mg kg⁻¹), which, whether wild-harvested or cultivated, do not stand out for their contribution to dietary intake of this element (Sánchez-Mata et al., 2016). Regarding Na, although it is an essential element for the human body, excessive intake can lead to significant health problems (Doyle and Glass, 2010). Many foods contribute to Na intake, not to mention the addition of sodium chloride (NaCl) to flavor foods. Consequently, excessive Na consumption is common. For this reason, it is recommended to prefer foods low in Na, and vegetables can generally be included among these. Except for some halophytic species, such as *Salicornia europaea* L. and *Crithmum maritimum* L., most leafy WEPs are below 1.2 g kg⁻¹ (Sánchez-Mata et al., 2016), which is the threshold under which a food can be considered as “low-Na content” according to Regulation (EC) 1924/2006. *H. radiata* microgreens and baby leaves were also below this limit; however, comparison with wild reference plants seems to indicate that cultivation led to an increase in Na content (Table 3). In comparison with crop species, *H. radiata* baby leaves showed slightly higher contents of Ca, K, Mg, P, and Na than those reported for green lettuce baby leaves (Santos et al., 2014). For microgreens, using radish as a reference crop (Xiao et al., 2016), *H. radiata* showed comparable K and Mg concentrations, was slightly richer in Ca and Na, and slightly poorer in P. Interestingly, microgreens exhibited lower contents of Ca, K, Mg, and P when grown under full-strength nutrient solution. Similar trends have been reported in spinach microgreens by Petropoulos et al., 2021. These authors attributed the lower concentrations under higher nutrient supply to a dilution effect associated with increased biomass production. However, the difference in yield between H and H/2 solutions was limited in the present study.

For essential trace elements (Table 4), our data indicate that *H. radiata* can be considered a good source, with the exception of Zn. In the cultivated plants, the content of this element was 1.4 mg kg⁻¹ on average, with no differences between growth stages or nutrient solution concentrations; in the wild reference plants, Zn reached 9.84 mg kg⁻¹, still below 15% of the NRV. Actually, Sánchez-Mata et al., 2016 claim that WEPs, exhibiting Zn levels usually below 10 mg kg⁻¹, are not

generally recognized as good sources of this element. Zinc contents reported in the literature for radish microgreens and lettuce baby leaves are 3.7 and 3.9 mg kg⁻¹, respectively (Xiao et al., 2016; Santos et al., 2014). *H. radiata* microgreens exceeded the NRVs for Cu, Fe, Mn, and Mo, whereas baby leaves showed concentrations close to the NRVs for Cu and Mn, and exceeded those for Fe and Mo. The latter element was relatively the most abundant, with values approximately one order of magnitude higher than the NRV. Molybdenum concentrations were also higher than those reported for microgreens and baby leaves of other WEPs, namely *Sanguisorba minor*, *Sinapis arvensis*, and *Taraxacum officinale* (Lenzi et al., 2019). In any case, as discussed later, its content was not hazardous for health. *H. radiata* microgreens were richer in Cu, Mn, and Mo than baby leaves and, conversely, contained Fe at lower concentrations. Differences in elemental composition between microgreens and baby leaf produce of the same species have been observed in both crop and wild plants, but not with univocal trends (Waterland et al., 2017; Lenzi et al., 2019; Ayeni, 2021; Martínez-Ispizua et al., 2022). For example, in *S. minor*, consistently with this study, baby leaves contained more Fe than microgreens; in contrast, in *T. officinale*, as well as in lettuce, Fe content was higher in microgreens than in baby leaves (Lenzi et al., 2019; Martínez-Ispizua et al., 2022).

To assess the contribution of *H. radiata* to human mineral requirements, EDI% values were calculated (Table 7). Despite some elements being more concentrated in microgreens, the smaller portion size resulted in lower EDI% compared to baby leaves, ranging from 0.23% (Zn) to 20.77% (Mo). In baby leaves, Zn and Mo represented the lowest and highest EDI% values among the analyzed minerals as well, with 0.61% and 41.54%, respectively. Baby leaves could also provide a notable contribution to the PRI for Fe (30.57%).

Due to their root-to-shoot translocation efficiency, many WEPs adapted to marginal soils are able to accumulate high levels of elements potentially toxic to human health in their aerial parts (Bandiera et al., 2016). This accumulation capacity must be carefully considered, especially when WEPs are collected or cultivated in polluted sites (Giacomino et al., 2016), but contamination may also occur in plants gathered from non-contaminated soils (Renna et al., 2015), and even under controlled cultivation conditions (Lenzi et al., 2019). For example, in a previous study, we found that microgreens of *Sanguisorba minor* grown hydroponically in a controlled environment contained Pb concentrations exceeding the maximum level established for leafy vegetables by Regulation (EU) 2023/915 (0.3 mg kg⁻¹) (Lenzi et al., 2019). Since water was excluded as a possible source of the metal, we hypothesized that traces of Pb could have originated from the fertilizers used to prepare the nutrient solution or from the substrate, namely vermiculite. In the present study, Pb concentrations in microgreens and baby leaves were well below the legal limit and below the LOD in the wild reference plants (Table 5). Similarly, the concentrations of the other potentially toxic elements measured in *H. radiata* did not raise health concerns, as HRI values were always below 1 (Table 8). Moreover, Cd content — together with Pb, the only other heavy metal regulated in leafy vegetables — was well below 0.1 mg kg⁻¹, which is the limit established by Regulation (EU) 2023/915. The most abundant element was Al, with values of approximately 30.4 mg kg⁻¹ on average in the cultivated plants, and 47.4 mg kg⁻¹ in the wild reference plants. Significant differences were observed in microgreens depending on the nutrient solution concentration, with higher values in H compared to H/2, suggesting that the likely source of Al contamination was the fertilizers used to prepare the solution. Nevertheless, the TWI established by EFSA (2008) would not be exceeded, even assuming a 100 g portion of the product, corresponding to portions two- and four-fold larger than those assumed in this study for baby leaf plants and microgreens, respectively. Aluminum content in *H. radiata* was comparable to that observed in *Sanguisorba minor*, *Sinapis arvensis*, and *Taraxacum officinale* microgreens and baby leaves grown under similar conditions (Lenzi et al., 2019).

In contrast to the wild reference plants, which contained negligible

amounts of nitrates, the levels detected in *H. radiata* microgreens and baby leaves ranged from 4286 mg kg⁻¹ in baby leaves grown in the H/2 solution to 7079 mg kg⁻¹ in microgreens under the H nutrient regime. Nitrate accumulation in vegetables raises concerns because of its potential adverse health implications (Santamaria, 2006). Considering the maximum levels established by Regulation (EU) 2023/915 for certain leafy vegetables, the nitrate content of cultivated *H. radiata* can be considered relatively high. The calculated HRI for nitrate in baby leaves was 1.05 (Table 8), only marginally above unity under the assumed consumption scenario of 50 g day⁻¹. This slight exceedance should not be interpreted as evidence of a health risk, but rather as an indication that nitrate accumulation in cultivated *H. radiata* warrants further investigation. Many studies have demonstrated that reducing nitrate concentrations in the nutrient solution, possibly by partially replacing it with ammonium nitrogen, can significantly decrease nitrate accumulation in the product; however, this strategy may lead to yield losses (Bian et al., 2020). In our study, the half-strength nutrient regime was sufficient to sustain yield while significantly reducing nitrate accumulation in baby leaves compared with the full-strength treatment. These findings suggest that further optimization of nitrogen management may represent a promising strategy to improve the nutritional quality of cultivated *H. radiata*. In particular, future studies should evaluate the effects of partially replacing nitrate with ammonium in the nutrient solution, while carefully assessing possible impacts on plant growth and yield. Environmental manipulation under controlled conditions, including optimization of light intensity, light spectrum, photoperiod, and harvest timing, has been shown to enhance nitrate assimilation and reduce nitrate accumulation in leafy vegetables, and therefore deserves investigation also in *H. radiata* production systems (Bian et al., 2020). Given the relatively low DLI applied in the present study (4.6 mol m⁻² day⁻¹), future studies should specifically evaluate the effects of higher PPFD and DLI on nitrate accumulation, biomass production, and nutritional quality of *H. radiata*. Temperature and CO₂ management may provide further opportunities to limit nitrate accumulation while maintaining crop productivity (Bian et al., 2020).

5. Conclusions

This work provides a scientific basis for the valorization of WEPs by linking biocultural heritage with the need to diversify and expand current cultivation systems. Our findings demonstrate that *Hyoseris radiata* microgreens and baby leaves can achieve promising yields under reduced nutrient inputs while providing valuable nutritional contributions to the human diet, thereby highlighting the species' potential as a novel leafy vegetable suitable for hydroponic production. No concerns related to heavy metal bioaccumulation emerged under the conditions tested. However, nitrate accumulation in hydroponically grown *H. radiata* warrants attention, as nitrate concentrations were relatively high under the cultivation conditions evaluated, although the calculated health risk index only marginally exceeded 1 under a conservative consumption scenario. Nevertheless, the ability of the crop to maintain productivity under the half-strength nutrient solution, together with the significant reduction in nitrate concentration observed in baby leaves, suggests that further optimization of cultivation practices may be feasible. Future studies should therefore investigate strategies such as optimizing nitrogen management (e.g., nitrate supply and the nitrate-to-ammonium ratio) and environmental conditions, particularly light intensity, light spectrum, and photoperiod. In particular, given the relatively low DLI applied in the present study, further research should evaluate the response of *H. radiata* to increasing PPFD and DLI, assessing their effects on biomass production, nitrate accumulation, and nutritional quality, in order to establish the light requirements of this species and identify cultivation conditions that optimize both yield and quality.

Funding

The research costs and the postdoctoral fellowships of S.T. and L.M. were funded by PNRR CN2 AGRITECH, Spoke 7, WP 7.2.2, “Promotion of wood and non-timber forest products, foods, and non-food chains (ecosystem services)”.

CRediT authorship contribution statement

Stefania Truschi: Writing – original draft, Investigation, Formal analysis. **Alfonso Crisci:** Writing – original draft, Formal analysis. **Piero Bruschi:** Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Ada Baldi:** Writing – review & editing, Investigation. **Lorenzo Marini:** Investigation, Conceptualization. **Tania Martellini:** Writing – original draft, Formal analysis. **Alessandra Cincinelli:** Formal analysis. **Anna Lenzi:** Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scienta.2026.115126](https://doi.org/10.1016/j.scienta.2026.115126).

Data availability

Data will be made available on request.

References

- Accogli, R., Nutricati, E., De Bellis, L., Renna, M., Luvisi, A., Negro, C., 2024. Diversity of *crithum maritimum* L. from Salento coastal area: a suitable species for domestication. *Horticulturae* 10, 81. <https://doi.org/10.3390/horticulturae10010081>.
- Aerts, R., Chapin III, F.S., 1999. The mineral nutrition of wild plants revisited: a re-evaluation of processes and patterns. *Adv. Ecol. Res.* 30, 1–67. [https://doi.org/10.1016/S0065-2504\(08\)60016-1](https://doi.org/10.1016/S0065-2504(08)60016-1).
- Ayeni, A., 2021. Nutrient content of micro/baby-greens and field-grown mature foliage of tropical spinach (*Amaranthus* sp.) and roselle (*Hibiscus sabdariffa* L.). *Foods* 10, 2546. <https://doi.org/10.3390/foods10112546>.
- Baldi, A., Bruschi, P., Campeggi, S., Egea, T., Rivera, D., Obón, C., Lenzi, A., 2022. The renaissance of wild food plants: insights from Tuscany (Italy). *Foods* 11, 300. <https://doi.org/10.3390/foods11030300>.
- Baldi, A., Truschi, S., Bruschi, P., Lenzi, A., 2023. Preliminary assessment of four wild leafy species to be used as baby salads. *Horticulturae* 9, 650. <https://doi.org/10.3390/horticulturae9060650>.
- Baldini, M., Fabietti, F., Giammarioli, S., Onori, R., Orefice, L., Stacchini, A., 1996. *Metodi di analisi utilizzati per il controllo chimico degli alimenti*. Rapporti. ISTISAN 96, 34. Istituto Superiore di Sanità, Rome, Italy.
- Bandiera, M., Dal Cortivo, C., Barion, G., Mosca, G., Vamerali, T., 2016. Phytoremediation opportunities with alimurgic species in metal-contaminated environments. *Sustainability* 8, 357. <https://doi.org/10.3390/su8040357>.
- Barros, L., Morales, P., Carvalho, A.M., Ferreira, I.C.F.R., 2016. Antioxidant potential of wild plant foods. In: Sánchez-Mata, M.D.C., Tardío, J. (Eds.), *Mediterranean Wild Edible Plants: Ethnobotany and Food Composition Tables*. Springer, New York, pp. 209–232.
- Benvenuti, S., Maggini, R., Pardossi, A., 2017. Agronomic, nutraceutical and organoleptic performances of wild herbs of ethnobotanical tradition. *Int. J. Veg. Sci.* 23, 270–281. <https://doi.org/10.1080/19315260.2016.1258605>.
- Benzie, I.F.F., Strain, J.J., 1996. The ferric reducing ability of plasma (FRAP) as a measure of antioxidant power. *Anal. Biochem.* 239, 70–76. <https://doi.org/10.1006/abio.1996.0292>.
- Bian, Z., Wang, Y., Zhang, X., Li, T., Grundy, S., Yang, Q., Cheng, R., 2020. A review of environment effects on nitrate accumulation in leafy vegetables grown in controlled environments. *Foods* 9, 732. <https://doi.org/10.3390/foods9060732>.
- Bosha, A., Dalbato, A.L., Tana, T., Mohammed, W., Tesfaye, B., Karlsson, L.M., 2016. Nutritional and chemical properties of fermented food of wild and cultivated genotypes of enset (*Ensete ventricosum*). *Food Res. Int.* 89, 806–811. <https://doi.org/10.1016/j.foodres.2016.10.016>.
- Botella, M.A., Hellín, P., Hernández, V., Dabauza, M., Robledo, A., Sánchez, A., Flores, P., 2024. Chemical composition of wild collected and cultivated edible plants (*Sonchus oleraceus* L. and *Sonchus tenerrimus* L.). *Plants* 13, 269. <https://doi.org/10.3390/plants13020269>.
- Bulgari, R., Baldi, A., Ferrante, A., Lenzi, A., 2017. Yield and quality of basil, swiss chard, and rocket microgreens grown in a hydroponic system. *N. Z. J. Crop. Hortic. Sci.* 45 (2), 119–129. <https://doi.org/10.1080/01140671.2016.1259642>.
- Cámara, M., Fernández-Ruiz, V., Ruiz-Rodríguez, B., 2016. Wild edible plants as sources of carotenoids, fibre, phenolics and other non-nutrient bioactive compounds. In: Sánchez-Mata, M.D.C., Tardío, J. (Eds.), *Mediterranean Wild Edible Plants: Ethnobotany and Food Composition Tables*. Springer, New York, NY, pp. 187–205.
- Caretto, S., Linsalata, V., Colella, G., Mita, G., Lattanzio, V., 2015. Carbon fluxes between primary metabolism and phenolic pathway in plant tissues under stress. *Int. J. Mol. Sci.* 16 (11), 26378–26394. <https://doi.org/10.3390/ijms161125967>.
- Carvalho, A.M., Barata, A.M., 2016. The consumption of wild edible plants. In: Ferreira, I.C.F.R., Morales, P., Barros, L. (Eds.), *Wild plants, Mushrooms and nuts: Functional Food Properties and Applications*, 1st edn. John Wiley & Sons, Ltd, Chichester, pp. 159–198.
- Ceccanti, C., Brizzi, A., Landi, M., Incrocci, L., Pardossi, A., Guidi, L., 2021. Evaluation of major minerals and trace elements in wild and domesticated edible herbs traditionally used in the mediterranean area. *Biol. Trace Elem. Res.* 199, 3553–3561. <https://doi.org/10.1007/s12011-020-02467-3>.
- Ceccanti, C., Landi, M., Incrocci, L., Pardossi, A., Venturi, F., Taglieri, I., Guidi, L., 2020. Comparison of three domestications and wild-harvested plants for nutraceutical properties and sensory profiles in five wild edible herbs. *Foods* 9, 1065. <https://doi.org/10.3390/foods9081065>.
- Chatzigianni, M., Alkhaled, B.A., Livieratos, I., Stamatakis, A., Ntatsi, G., Savvas, D., 2018. Impact of nitrogen source and supply level on growth, yield and nutritional value of two contrasting ecotypes of *cichorium spinosum* L. grown hydroponically. *J. Sci. Food Agric.* 98, 1615–1624. <https://doi.org/10.1002/jsfa.8636>.
- Collado-González, J., Piñero, M.C., Ojalora, G., López-Marín, J., Del Amor, F.M., 2022. Assessing optimal nitrate/ammonium ratios in baby-leaf lettuce under elevated CO₂. *PLoS One* 17, e0278309. <https://doi.org/10.1371/journal.pone.0278309>.
- Conversa, G., Bonasia, A., Lazzizzera, C., Elia, A., 2021a. Soilless cultivation system, electrical conductivity of nutrient solution, and growing season on yield and quality of baby-leaf oak-leaf lettuce. *Agronomy* 11, 1220. <https://doi.org/10.3390/agronomy11061220>.
- Conversa, G., Bonasia, A., Lazzizzera, C., La Rotonda, P., Elia, A., 2021b. Reduction of nitrate content in baby-leaf lettuce and cichorium endivia through the soilless cultivation system, electrical conductivity and management of nutrient solution. *Front. Plant Sci.* 12, 645671. <https://doi.org/10.3389/fpls.2021.645671>.
- Dantas, T., Costa, E., da Silva, J.B.M., Binotti, F.F.S., Vendruscolo, E.P., Vieira, G.H.C., Ribeiro, F.C.S., 2024. Effect of different substrates and protected environments on growth, chlorophyll and carotenoid contents of kale microgreens and baby leaf. *Int. J. Agron.* 2024, 8842753. <https://doi.org/10.1155/2024/8842753>.
- Di Bella, M.C., Niklas, A., Toscano, S., Picchi, V., Romano, D., Lo Scalzo, R., Branca, F., 2020. Morphometric characteristics, polyphenols and ascorbic acid variation in *Brassica oleracea* L. novel foods: sprouts, microgreens and baby leaves. *Agronomy* 10, 782. <https://doi.org/10.3390/agronomy10060782>.
- Di Gioia, F., Renna, M., Santamaria, P., 2017. Sprouts, microgreens and baby leaf vegetables. In: Yildiz, F., Wiley, R.C. (Eds.), *Minimally Processed Refrigerated Fruits and Vegetables*. Springer, Boston, pp. 403–432.
- Doyle, M.E., Glass, K.A., 2010. Sodium reduction and its effect on food safety, food quality and human health. *Compr. Rev. Food Sci. Food Saf.* 9, 44–56. <https://doi.org/10.1111/j.1541-4337.2009.00096.x>.
- Ebert, A.W., Wu, T.H., Yang, R.Y., 2014. Amaranth sprouts and microgreens - a homestead vegetable production option to enhance food and nutrition security in the rural-urban continuum. In: *Proceedings of the Regional Symposium on Sustaining Small-Scale Vegetable Production and Marketing Systems for Food and Nutrition Security (SEAVEG 2014)*. Bangkok, Thailand, pp. 233–244, 25–27 February 2014.
- EFSA - European Food Safety Authority, 2008. Safety of aluminium from dietary intake - scientific opinion of the panel on food Additives, Flavourings, processing aids and food contact materials (AFC). *EFSA J.* 6, 754. <https://doi.org/10.2903/j.efsa.2008.754>, 2008.
- EFSA - Panel on Food Additives and Nutrient Sources added to Food (ANS), 2017. Re-evaluation of sodium nitrate (E 251) and potassium nitrate (E 252) as food additives. *EFSA J.* 15 (6), e04787. <https://doi.org/10.2903/j.efsa.2017.4787>.
- El-Masry, S., Ghazy, N.M., Zdero, C., Bohlmann, F., 1983. An acetylenic triol from *hyoscyamus* L. *Phytochemistry* 22, 592–593. [https://doi.org/10.1016/0031-9422\(83\)83055-6](https://doi.org/10.1016/0031-9422(83)83055-6).
- El-Nakheel, C., Pannico, A., Graziani, G., Kyriacou, M.C., Gaspari, A., Ritieni, A., Rouphael, Y., 2021. Nutrient supplementation configures the bioactive profile and production characteristics of brassica microgreens. *Agronomy* 11, 346. <https://doi.org/10.3390/agronomy11020346>.
- Elgueta, S., Fuentes, M., Valenzuela, M., Zhao, G., Liu, S., Lu, H., Correa, A., 2019. Pesticide residues in ready-to-eat leafy vegetables from markets of Santiago, Chile, and consumer risk. *Food Addit. Contam. Part B* 12, 259–267. <https://doi.org/10.1080/19393210.2019.1625975>.
- Esposito, M., De Roma, A., Cavallo, S., Miedico, O., Chiaravalle, E., Soprano, V., Baldi, L., Gallo, P., 2019. Trace elements in vegetables and fruits cultivated in southern Italy. *J. Food Compos. Anal.* 84, 103302. <https://doi.org/10.1016/j.jfca.2019.103302>.
- European Committee for Standardization, 2014. EN 13805: Foodstuffs — Determination of trace elements — Pressure digestion. CEN, Brussels.
- Fayezzadeh, M.R., Ansari, N.A., Sourestani, M.M., Hasanuzzaman, M., 2023. Balancing yield and antioxidant capacity in basil microgreens: an exploration of nutrient

- solution concentrations in a floating system. *Agriculture* 13, 1691. <https://doi.org/10.3390/agriculture13091691>.
- Fenner, M., Thompson, K., 2005. *The Ecology of Seeds*. Cambridge University Press, Cambridge.
- García-Herrera, P., Sánchez-Mata, M.D.C., 2016. The contribution of wild plants to dietary intakes of micronutrients (II): mineral elements. In: Sánchez-Mata, M.D.C., Tardío, J. (Eds.), *Mediterranean Wild Edible Plants: Ethnobotany and Food Composition Tables*. Springer, New York, pp. 141–171.
- Geraci, A., Amato, F., Di Noto, G., Bazan, G., Schicchi, R., 2018. The wild taxa utilized as vegetables in Sicily (Italy): a traditional component of the mediterranean diet. *J. Ethnobiol. Ethnomed.* 14, 14. <https://doi.org/10.1186/s13002-018-0215-x>.
- Ghoora, M.D., Babu, D.R., Srividya, N., 2020. Nutrient composition, oxalate content and nutritional ranking of ten culinary microgreens. *J. Food Compos. Anal.* 91, 103495. <https://doi.org/10.1016/j.jfca.2020.103495>.
- Giacomino, A., Malandrino, M., Colombo, M.L., Miaglia, S., Maimone, P., Blancato, S., Conca, E., Abollino, O., 2016. Metal content in dandelion leaves: influence of vehicular traffic and safety upon consumption as food. *J. Chem.* 2016, 1–9. <https://doi.org/10.1155/2016/9842987>.
- Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ.* 41, 393–408. [https://doi.org/10.1016/S0921-8009\(02\)00089-7](https://doi.org/10.1016/S0921-8009(02)00089-7).
- Guarrera, P., 2006. *Usi e Tradizioni della Flora Italiana. Medicina popolare ed Etnobotanica*. Aracne Editrice S.r.l., Rome.
- Guarrera, P.M., Savo, V., 2016. Wild food plants used in traditional vegetable mixtures in Italy. *J. Ethnopharmacol.* 185, 202–234. <https://doi.org/10.1016/j.jep.2016.02.050>.
- International Organization for Standardization, 2016. *ISO 17294-2: Water quality — Application of inductively coupled plasma mass spectrometry (ICP-MS) — Part 2: Determination of selected elements including uranium isotopes*. ISO, Geneva.
- Kassambara, A., Mundt, F., 2020. Factoextra: extract and visualize the results of multivariate data analyses (Version 1.0.7) [software]. <https://doi.org/10.32614/CRAN.package.factoextra>.
- Keutgen, N., Hausknecht, M., Tomaszewska-Sowa, M., Keutgen, A.J., 2021. Nutritional and sensory quality of two types of cress microgreens depending on mineral nutrition. *Agronomy* 11, 1110. <https://doi.org/10.3390/agronomy11061110>.
- Kim, D.E., Shang, X., Assefa, A.D., Keum, Y.S., Saini, R.K., 2018. Metabolite profiling of green, green/red, and red lettuce cultivars: variation in health beneficial compounds and antioxidant potential. *Food Res. Int.* 105, 361–370. <https://doi.org/10.1016/j.foodres.2017.11.028>.
- Kromberga, A., Nakurte, I., Kaļāne, L., Vecvanags, A., Jakovels, D., Filipovs, J., Mezaka, I., 2023. Cultivation potential of taraxacum campyloides wild populations: morphological and biochemical variation. *Plant Genet. Resour.* 21, 71–80. <https://doi.org/10.1017/S1479262123000436>.
- Lenzi, A., Orlandini, A., Bulgari, R., Ferrante, A., Bruschi, P., 2019. Antioxidant and mineral composition of three wild leafy species: a comparison between microgreens and baby greens. *Foods* 8, 487. <https://doi.org/10.3390/foods8100487>.
- Mallor, C., Bertolín, J.R., Paracuellos, P., Juan, T., 2023. Nutraceutical potential of leafy vegetables landraces at microgreen, baby, and adult stages of development. *Foods* 12, 3173. <https://doi.org/10.3390/foods12173173>.
- Maphosa, Y., Jideani, V.A., 2017. The role of legumes in human nutrition. In: Hueda, M. C. (Ed.), *Functional Food – Improve Health Through Adequate Food*. InTechOpen, London, pp. 103–121.
- Martínez-Ispizua, E., Calatayud, Á., Marsal, J.I., Cannata, C., Basile, F., Abdelkhalik, A., et al., 2022. The nutritional quality potential of microgreens, baby leaves, and adult lettuce: an underexploited nutraceutical source. *Foods* 11, 423. <https://doi.org/10.3390/foods11030423>.
- Nicola, S., Egea-Gilbert, C., Niñirola, D., Conesa, E., Pignata, G., Fontana, E., Fernández, J.A., 2015. Nitrogen and aeration levels of the nutrient solution in soilless cultivation systems as important growing conditions affecting inherent quality of baby leaf vegetables: a review. *Acta Hort.* 1099, 167–177. <https://doi.org/10.17660/ActaHortic.2015.1099.17>.
- Orlandi, F., Proietti, C., Ranfa, A., Trabalzini, A., Maurizi, A., Coli, R., Fornaciari, M., 2024. Nutraceutical compounds of edible wild plants collected in central Italy. *J. Wildl. Biodivers.* 8, 15–30. <https://doi.org/10.5281/zenodo.13820009>.
- Paradiso, V.M., Castellino, M., Renna, M., Gattullo, C.E., Calasso, M., Terzano, R., Allegratta, I., Leoni, B., Caponio, F., Santamaria, P., 2018. Nutritional characterization and shelf-life of packaged microgreens. *Food Funct.* 9, 5629–5640. <https://doi.org/10.1039/C8FO01182F>.
- Pardo-de-Santayana, M., Tardío, J., Blanco, E., Carvalho, A.M., Lastra, J.J., San Miguel, E., Morales, R., 2007. Traditional knowledge of wild edible plants used in the northwest of the Iberian Peninsula (Spain and Portugal): a comparative study. *J. Ethnobiol. Ethnomed.* 3, 27. <https://doi.org/10.1186/1746-4269-3-27>.
- Paura, B., Di Marzio, P., Salerno, G., Brugiapaglia, E., Bufano, A., 2021. Design a database of Italian vascular alimurgic flora (AlimurgITA): preliminary results. *Plants* 10, 743. <https://doi.org/10.3390/plants10040743>.
- Petropoulos, S.A., El-Nakhel, C., Graziani, G., Kyriacou, M.C., Rouphael, Y., 2021. Effects of nutrient solution feeding regime on spinach microgreens. *Horticulturae* 7, 162. <https://doi.org/10.3390/horticulturae7070162>.
- Petropoulos, S.A., Fernandes, Á., Dias, M.I., Vasilakoglou, I.B., Petrotos, K., Barros, L., Ferreira, I.C.F.R., 2019. Nutritional value, chemical composition and cytotoxic properties of common purslane. *Antioxidants* 8, 293. <https://doi.org/10.3390/antiox8080293>.
- Petropoulos, S.A., Fernandes, Á., Ntatsi, G., Levizou, E., Barros, L., Ferreira, I.C.F.R., 2016. Nutritional profile and chemical composition of *cichorium spinosum* ecotypes. *LWT – Food Sci. Technol.* 73, 95–101. <https://doi.org/10.1016/j.lwt.2016.05.046>.
- Pinela, J., Carvalho, A.M., Ferreira, I.C., 2017. Wild edible plants: nutritional and toxicological characteristics, retrieval strategies and importance for today's society. *Food Chem. Toxic.* 110, 165–188. <https://doi.org/10.1016/j.fct.2017.10.020>.
- Pinto, E., Almeida, A.A., Aguiar, A.A., Ferreira, I.M.P.L.V.O., 2015. Comparison between the mineral profile and nitrate content of microgreens and mature lettuces. *J. Food Compos. Anal.* 37, 38–43. <https://doi.org/10.1016/j.jfca.2014.06.018>.
- Puccinelli, M., Pezzarossa, B., Pintimalli, L., Malorgio, F., 2021. Selenium biofortification of three wild species, *Rumex acetosa* L., *Plantago coronopus* L., and *portulaca oleracea* L., grown as microgreens. *Agronomy* 11, 1155. <https://doi.org/10.3390/agronomy11061155>.
- R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. <https://doi.org/10.32614/src>.
- Raju, M., Varakumar, S., Lakshminarayana, R., Krishnakantha, T.P., Baskaran, V., 2007. Carotenoid composition and vitamin a activity of medicinally important green leafy vegetables. *Food Chem.* 101, 1598–1605. <https://doi.org/10.1016/j.foodchem.2006.04.015>.
- Regulation (EC) 1924/2006 of the European Parliament and of the Council of 20 December 2006 on nutrition and health claims made on foods; Off. J. Eur. Union, L 404, pp. 9–25. <https://eur-lex.europa.eu/legalcontent/EN/ALL/?uri=CELEX%3A02006R1924-20121129> (accessed 9 April 2026).
- Regulation (EU) 1169/2011; Regulation (EU) 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers, Off. J. Eur. Union, L 304, pp. 18–63; Available from: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:304:0018:0063:EN:PDF> (accessed 9 April 2026).
- Regulation (EU) 2023/915, Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006; Off. J. Eur. Union, L119, 103–157.
- Renna, M., Castellino, M., Leoni, B., Paradiso, V.M., Santamaria, P., 2018. Microgreens production with low potassium content for patients with impaired kidney function. *Nutrients* 10, 675. <https://doi.org/10.3390/nu10060675>.
- Renna, M., Cocozza, C., Gonnella, M., Abdelrahman, H., Santamaria, P., 2015. Elemental characterization of wild edible plants from countryside and urban areas. *Food Chem.* 177, 29–36. <https://doi.org/10.1016/j.foodchem.2014.12.069>.
- Sánchez-Mata, M.D.C., Matallana-González, M.C., Morales, P., 2016. The contribution of wild plants to dietary intakes of micronutrients (I): vitamins. In: Sánchez-Mata, M.D.C., Tardío, J. (Eds.), *Mediterranean Wild Edible Plants: Ethnobotany and Food Composition Tables*. Springer, New York, pp. 111–139.
- Santamaria, P., 2006. Nitrate in vegetables: toxicity, content, intake and EC regulation. *J. Sci. Food Agric.* 86, 10–17. <https://doi.org/10.1002/jsfa.2351>.
- Santos, J., Oliva-Teles, M.T., Delerue-Matos, C., Oliveira, M.B.P.P., 2014. Multi-elemental analysis of “ready-to-eat” baby leaf vegetables using microwave digestion and high-resolution continuum source atomic absorption spectrometry. *Food Chem.* 151, 311–316. <https://doi.org/10.1016/j.foodchem.2013.11.083>.
- Schulp, C.J., Thuiller, W., Verburg, P.H., 2014. Wild food in Europe: a synthesis of knowledge and data of terrestrial wild food as an ecosystem service. *Ecol. Econ.* 105, 292–305. <https://doi.org/10.1016/j.ecolecon.2014.06.018>.
- Sicari, V., Loizzo, M.R., Sanches Silva, A., Romeo, R., Spampinato, G., Tundis, R., Leporini, M., Musarella, C.M., 2020. The effect of blanching on phytochemical content and bioactivity of *Hypochaeris* and *Hyoseris* species. *Foods* 10, 32. <https://doi.org/10.3390/foods10010032>.
- Simko, I., 2019. Genetic variation and relationship among content of vitamins, pigments, and sugars in baby leaf lettuce. *Food Sci. Nutr.* 7, 3317–3326. <https://doi.org/10.1002/fsn3.1196>.
- Società Italiana di Nutrizione Umana, 2024. *LARN: Livelli di Assunzione di Riferimento di Nutrienti ed Energia per La Popolazione Italiana (V revisione)*. SICS Editore, Milano.
- Song, J., Huang, H., Song, S., Zhang, Y., Su, W., Liu, H., 2020. Effects of photoperiod interacted with nutrient solution concentration on nutritional quality and antioxidant and mineral content in lettuce. *Agronomy* 10, 920. <https://doi.org/10.3390/agronomy10070920>.
- Tadolini, B., Juliano, C., Piu, L., Franconi, F., Cabrini, L., 2000. Resveratrol inhibition of lipid peroxidation. *Free Radic. Res.* 33, 105–114. <https://doi.org/10.1080/10715760000300661>.
- Tardío, J., Pardo-de-Santayana, M., 2016. Ethnobotanical analysis of wild fruits and vegetables traditionally consumed in Spain. In: Sánchez-Mata, M.D.C., Tardío, J. (Eds.), *Mediterranean Wild Edible Plants: Ethnobotany and Food Composition Tables*. Springer, New York, pp. 57–79.
- Treadwell, D., Hochmuth, R., Landrum, L., Laughlin, W., 2020. Microgreens: a new specialty crop. University of Florida IFAS Extension HS1164. <https://doi.org/10.32473/edis-hs1164-2020>.
- Uarotta, V.G., Stefen, D.L.V., Leolato, L.S., Gindri, D.M., Nerling, D., 2018. Revisiting carotenoids and their role in plant stress responses: from biosynthesis to plant signaling mechanisms during stress. In: Gupta, D.K., Palma, J.M., Corpea, F.J. (Eds.), *Antioxidants and Antioxidant Enzymes in Higher Plants*. Springer, Cham, pp. 207–232.
- US Environmental Protection Agency (EPA), 2023. Integrated risk information system (IRIS). Available from: <https://iris.epa.gov/> accessed 7 April 2026.
- Vanzani, P., Rossetto, M., De Marco, V., Sacchetti, L.E., Paoletti, M.G., Rigo, A., 2011. Wild mediterranean plants as traditional food: a valuable source of antioxidants. *J. Food Sci.* 76, C46–C51. <https://doi.org/10.1111/j.1750-3841.2010.01949.x>.
- Vastakaitė-Kairienė, V., Brazaitytė, A., Viršilė, A., Samuolienė, G., Miliauskienė, J., Jankauskienė, J., Novickovas, A., Duchovskis, P., 2020. The nutritional value of Brassica leafy greens in different growth stages. *Acta Hort.* 1271, 455–464. <https://doi.org/10.17660/ActaHortic.2020.1271.62>.

- Verma, S., Kumar, A., Kumari, M., Kumar, N., Hansda, S., Saurabh, A., Poonia, S., Rathore, S.D., 2024. A review on hydroponics and vertical farming for vegetable cultivation: innovations and challenges. *J. Exp. Agric. Int.* 46, 801–821. <https://doi.org/10.9734/jeai/2024/v46i123190>.
- Vignesh, A., Amal, T.C., Sarvalingam, A., Vasanth, K., 2024. A review on the influence of nutraceuticals and functional foods on health. *Food Chem. Adv.* 5, 100749. <https://doi.org/10.1016/j.focha.2024.100749>.
- Vitiello, M., Pecoraro, M., De Leo, M., Camangi, F., Parisi, V., Donadio, G., et al., 2024. Chemical profiling, antioxidant, and anti-inflammatory activities of *Hyoseris radiata* L., a plant used in the phytoalimurgic tradition. *Antioxidants* 13, 111. <https://doi.org/10.3390/antiox13010111>.
- Voutsinos-Frantzis, O., Savvas, D., Antoniadou, N., Karavidas, I., Ntansi, T., Sabatino, L., Ntatsi, G., 2024. Innovative cultivation practices for reducing nitrate content in baby leaf lettuce grown in a vertical farm. *Horticulturae* 10, 375. <https://doi.org/10.3390/horticulturae10040375>.
- Waterland, N.L., Moon, Y., Tou, J.C., Kim, M.J., Pena-Yewtukhiw, E.M., Park, S., 2017. Mineral content differs among microgreen, baby leaf and adult stages in kale. *HortScience* 52, 566–571. <https://doi.org/10.21273/HORTSCI11499-16>.
- Wieth, A.R., Pinheiro, W.D., Duarte, T.D.S., 2019. Purple cabbage microgreens grown in different substrates and nutritive solution concentrations. *Rev. Caatinga* 32, 976–985. <https://doi.org/10.1590/1983-21252019v32n414rc>.
- Xiao, Z., Codling, E.E., Luo, Y., Nou, X., Lester, G.E., Wang, Q., 2016. Microgreens of Brassicaceae: mineral composition and content of 30 varieties. *J. Food Compos. Anal.* 49, 87–93. <https://doi.org/10.1016/j.jfca.2016.04.006>.
- Xiao, Z., Lester, G.E., Luo, Y., Wang, Q., 2012. Assessment of vitamin and carotenoid concentrations of emerging food products: edible microgreens. *J. Agric. Food Chem.* 60 (31), 7644–7651. <https://doi.org/10.1021/jf300459b>.
- Yamada, K., Osakabe, Y., 2018. Sugar compartmentation as an environmental stress adaptation strategy in plants. *Semin. Cell Dev. Biol.* 83, 106–114. <https://doi.org/10.1016/j.semcdb.2017.12.015>.
- Zou, L., Tan, W.K., Du, Y., Lee, H.W., Liang, X., Lei, J., Ong, C.N., 2021. Nutritional metabolites in *Brassica rapa* subsp. *Chinensis* at three growth stages. *Food Chem.* 357, 129535. <https://doi.org/10.1016/j.foodchem.2021.129535>.