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Fruit composition profile of pepper, tomato and eggplant varieties grown under uniform conditions

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ABSTRACT

The study of the diversity within and between major *Solanaceae* crops (pepper, tomato, eggplant) is of interest for the selection and development of balanced diets. We have measured thirty-six major fruit composition traits, encompassing sugars, organic acids, antioxidants and minerals, in a set of 10 accessions per crop for pepper, tomato and eggplant, grown under the same cultivation conditions. The aim was to evaluate the diversity within species and to provide an accurate comparison of fruit composition among species by reducing to a minimum the environmental effect. Pepper, tomato and eggplant had a clearly distinct composition profile. Pepper showed the highest average content in total sugars and organic acids. Fructose and glucose were the major sugar compounds in the three species, although in pepper and tomato sucrose was present only in trace amounts. Citric acid was the major organic acid in pepper and tomato, while in eggplant it was malic acid. Pepper and eggplant had the highest total antioxidant activity. Vitamin C content was much higher in pepper than in tomato and eggplant, while eggplant accumulated high concentrations of chlorogenic acid. Furthermore, eggplant was the species with higher content in most minerals, particularly for K, Mg and Cu, while pepper was the richest in Fe. Due to their complementary nutritional profiles, a combined regular consumption of the three vegetables would supply more than 20% of the Dietary Reference Intake of several of the analysed phytochemicals. The large diversity within each species is of interest for selecting varieties with better nutritional and organoleptic profiles, as well as for breeding new cultivars.

1. Introduction

The *Solanaceae* family includes some of the world's most economically important berry-producing vegetables such as pepper (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.) and eggplant (*Solanum melongena* L.) (Olmstead et al., 2008). In 2019, they ranked seventh ($38{\cdot}10^6$ t), first ($181{\cdot}10^6$ t) and fifth ($55{\cdot}10^6$ t), respectively, among vegetables for world total production (FAOSTAT, 2019). The fruits of pepper, tomato and eggplant are part of the cuisine of the whole world, although the predominant form of consumption varies among different cultures. Fruits of eggplant are harvested and consumed physiologically immature, while fruits of tomato are usually consumed at physiological maturity, and fruits of pepper can be consumed at both maturity stages. Both peppers and tomatoes are consumed fresh, cooked or dried; while eggplants are generally cooked. A daily dietary intake of these and other vegetables is highly recommended since they represent low-calorie nutrient-dense foods, constituting an important source of fibre, vitamins, minerals and a diverse array of other health-promoting phytochemicals like phenolic acids and flavonoids (Bursać Kovačević et al., 2020; Yahia, García-Solís, & Celis, 2019).

Many studies on chemical composition of several cultivars of pepper, tomato and eggplant have been carried out over the last years. These studies reveal that peppers represent an outstanding source of vitamin C, flavonols (quercetin, kaempferol) and flavones (luteolin, apigenin) (Chassy, Bui, Renaud, Van Horn, & Mitchell, 2006; Fratianni et al., 2020; Lemos, Reimer, & Wormit, 2019; Mennella et al., 2018; Wahyuni,

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Ballester, Sudarmonowati, Bino, & Bovy, 2013), and contain more than 20 different carotenoids (Giuffrida et al., 2013). Based on the published Dietary Reference Intake (DRI) values (Institute of Medicine, 2006), a portion of 100 g of pepper usually contributes over 100% to the daily intake of vitamin C and tocopherol, and provides 5–10% of provitamin A intake (Wahyuni et al., 2013). Tomatoes appear as the main source of lycopene in diet, but they also constitute an important source of vitamin C, E and flavonoids naringenin and quercetin-3-*O*-rutinoside (rutin) (Martí et al., 2018; Siddiqui, Ayala-Zavala, & Dhua, 2015; Slimestad, Fossen, & Verheul, 2008). A serving size (200 g) of fresh tomatoes has been reported to contribute mainly to the intakes of fibre and antioxidant compounds, providing 30 to 36% of the Recommended Dietary Allowance (RDA) for vitamin C; but it also contributes in a moderate proportion to the reference intake values of minerals, providing 10% of the Adequate Intake (AI) for K and 5–10% of the RDA for P and Mg (Casiraghi, Ribas-Agusti, Cáceres, Marfà, & Castellari, 2013; Frusciante et al., 2007; Mohammed, Smit, Pawelzik, Keutgen, & Horneburg, 2020). Eggplants stand out for their high content in phenolics, mostly anthocyanins in the purple-coloured peel, and chlorogenic acid in the flesh (Docimo et al., 2016; García-Salas, Gómez-Caravaca, Morales-Soto, Segura-Carretero, & Fernández-Gutiérrez, 2014; Singh et al., 2009; Whitaker & Stommel, 2003), but they are also known for being a good source of minerals (Ayaz et al., 2015; Raigón, Rodríguez-Burruezo, & Prohens, 2010). In that way, in a previous comprehensive fruit quality study of 31 varieties of eggplant, a portion of 100 g of fruit was reported to provide 7.7–13.5% of the estimated daily intake for phenolics; but it also contributed 2.8–6.2% to P RDA, 3.3–5.9% to K RDA, and 4.3–9.7% to Cu RDA (Raigón, Prohens, Muñoz-Falcón, & Nuez, 2008).

In the last decade, secondary metabolites such as phenolic acids and flavonoids have garnered increasing attention in both food research and plant breeding due to their bioactive role and health-promoting function (Pott, Osorio, & Vallarino, 2019). Those compounds have shown antioxidant, antitumoral, anti-inflammatory and/or anti-microbial activity in several assays (Frutos, Rincón-Frutos, & Valero-Cases, 2019; Granger & Eck, 2018; Kelkel, Schumacher, Dicato, & Diederich, 2011; Kleemann et al., 2011; Sato et al., 2011), which contribute to the health benefits associated to the consumption of peppers, tomatoes and eggplants. Most of those benefits are related to protective effects, lowering the risk of cardiovascular, neurodegenerative and chronic diseases, including metabolic disorders and different types of cancer (Yahia et al., 2019). Furthermore, breeding for high content in bioactive compounds would lead to higher resilience to abiotic and biotic stresses, since those metabolites are involved in plant defence mechanisms (Yang et al., 2018).

Chemical composition of fruits is strongly dependent on the environmental and cultivation conditions (light, temperature, humidity, cultural practices, etc.). In this way, Tripodi et al. (2018) found the environment as an important source of variation, accounting for more than 30%, for carotenoids, vitamin C and tocopherols accumulation in fruits of hot pepper cultivated in two contrasting locations. Lower carotenoids content in fruit, but higher concentration of glucose and antioxidant activity were reported in the Mediterranean long shelf-life tomato under greenhouse conditions compared to open field cultivation by Figàs et al. (2018). Stommel, Whitaker, Haynes, and Prohens (2015) also found a highly significant genotype × environment effect for content in phenolics in several varieties of eggplant, with two- to four-fold differences between mean values in two different cultivation sites. In addition, some studies aiming at assessing the genotype effect on composition traits reported a wide diversity among varieties for each of the three crops. In this way, Fratianni et al. (2020) found different polyphenol profiles among 14 traditional pepper varieties, Casals, Rivera, Sabaté, del Castillo, and Simó (2019) found considerable variation for taste-related compounds among tomato varieties within two different cultivar groups, and San José, Sánchez, Cámara, and Prohens (2013) reported a wide diversity among seven eggplant cultivar groups for fibre, protein, carbohydrates, phenolics and vitamin C. Hence, environmental and genetic differences make it difficult to compare composition profiles from different studies. To our knowledge, no evaluation and comparison of fruit composition has been performed for a diverse set of these three crops grown under the same conditions.

In the present work, we have measured thirty-six major relevant compounds and parameters related to nutritional and organoleptic quality, including sugars, organic acids, β-carotene, vitamin C, phenolic acids, flavonoids and minerals, in fresh fruits at commercial ripeness of ten varieties for each of pepper, tomato and eggplant, grown under the same environmental conditions and organic agricultural practices. We have also evaluated the contribution of each crop to the available RDA or AI for several compounds analysed. The main objective was to provide insight into the variation of the nutritional and organoleptic quality profile of these three solanaceous crops.

2. Materials and methods

2.1. Plant material and cultivation conditions

A total of 30 varieties of pepper ($n = 10$; P_ codes), tomato ($n = 10$; T_ codes) and eggplant ($n = 10$; E_ codes) were evaluated in the present study. The varieties selected were representative of the diversity of each species. A representative picture of fruits of the varieties used, including accession names, is displayed in Fig. 1. Five plants per accession were grown in open field, in the spring-summer of 2017. For each species, the plants were distributed in a completely randomized design in a plot located in Burriana (Valencian Region, Mediterranean coast of Spain). The cultivation was carried out under organic farming following the standard horticultural management practices used in the area. The same conditions were applied to the three crops, since they have similar ranges of nutrition, temperature, soil pH requirements for open field cultivation during the spring-summer season (Rubatzky & Yamaguchi, 1997). In addition, we did not observe that any of the three crops had suboptimal growth or production. The plants were staked with canes and trained, and spaced at 0.50-m and 1.5-m intervals within and between rows, respectively. Flood irrigation was provided as needed to avoid water deficit stress and to compensate the crops evapotranspiration. Fertilization was provided by a single organic basal dressing consisting of chicken manure (N-P-K composition of 5–2-1) at a dose of 500 g/m^2. Soil texture was clay loam, which represents a well-balanced soil with intermediate compaction degree, avoiding rapid loss of nutrients and water and allowing proper aeration (Tracy, Black, Roberts, & Mooney, 2013). Average temperature during the cultivation period was 23.9 °C, and varied between 17.0 °C and 29.9 °C. Relative humidity was 64.4% in average, and ranged between 39.3% and 86.7%. May and June were the months with the highest mean radiation, with 27.2 MJ m^{-2} and 28.0 MJ m^{-2}, respectively, and this parameter declined during the following months, to an average of 17.4 MJ m^{-2} in September. Pluviometry was scarce and mostly concentrated on May 18th (8.5 mm), June 4th (20.4 mm) and August 29th (13.8 mm).

2.2. Sample preparation and metabolites analyses

2.2.1. Sample preparation

Fruits of pepper and tomato accessions were harvested at the red stage of maturity, which determines both commercial and physiological ripeness (Grierson & Kader, 1986; Harel, Parmet, & Edan, 2020). On the other hand, fruits of eggplant accessions were collected at the commercial ripeness stage, i.e., when fruits reached full size but yet physiologically immature. Three replicates per accession were taken, each one corresponding to 3–5 fruits from different plants. The fruits collected were washed, cut in pieces and seeds were eliminated. For each replicate, three differently processed samples were obtained for subsequent chemical analyses: a) liquid extract was collected using a HR 1832/45 domestic juice extractor (Philips, Eindhoven, Netherlands); b) freeze-dried and homogenized material was obtained using a VirTis Genesis lyophilizer (SP Scientific, Warminster, PA, USA) and a

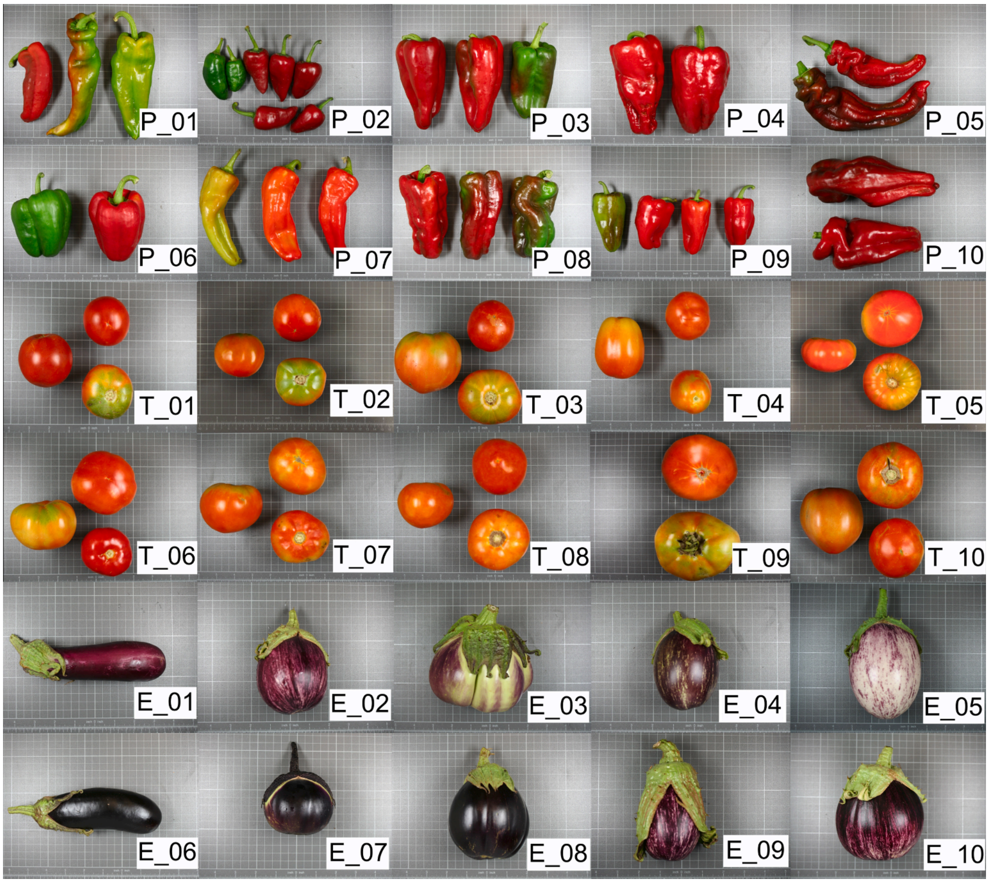

Fig. 1. Representative fruits of the 10 varieties of pepper (P_ codes), tomato (T_ codes) and eggplant (E_ codes) used for the evaluation of chemical composition in the present work. The grid cells in the pictures measure 1 × 1 cm.

908,503,000 domestic grinder (Taurus, Oliana, Spain); and, c) dried material in a drying oven Digit DOD-20 (Raypa, Terrassa, Spain) at 70 °C up to constant weight was collected and powdered. Every trait analysed, with abbreviations used in Tables and Figures and units in which they are expressed, are listed in Table 1.

2.2.2. *Proximate traits*

Dry matter was calculated as 100 × (dry weight/fresh weight). Crude protein content in fruit was estimated as 6.25 × total nitrogen, which was measured from 0.4 g of oven-dried powdered samples, through the Kjeldahl method (AOAC International, 2016) using a Kjeltec 2100 Distillation Unit (Foss Tecator, Högamäs, Sweden). Soluble solids content was measured using liquid extracts and a HI 96,801 digital refractometer (HANNA instruments, Padua, Italy).

2.2.3. *Sugars and organic acids*

Sugars (fructose, glucose, sucrose) and organic acids (citric, malic) were identified by HPLC using a 1220 Infinity LC System (Agilent Technologies, Santa Clara, CA, USA) equipped with a binary pump, an automatic injector and a UV detector. Quantification was based on calibration curves performed using known concentrations of standard references of each compound (Sigma-Aldrich, Saint Louis, MO, USA). For those analyses, aliquots of liquid extract were centrifuged for 5 min at 10,000 rpm and the supernatant diluted with water by ¼ and ½ only for pepper and tomato samples, respectively. The diluted samples were filtered through 0.22 µm PVDF MILLEX-GV filters (Merck Millipore, Burlington, MA, USA). The same sample was used to perform the analysis of sugars and organic acids. Fructose, glucose and sucrose were separated using a Luna® Omega SUGAR column (3 µm; 151 150 × 4.6 mm; Phenomenex, Torrance, CA, USA). An isocratic gradient of the mobile phase 75% solvent A (acetonitrile): 25% solvent B (HPLC-grade water) was applied. The flow rate was 1 mL min^{-1}. Sugars were subsequently detected by refractive index using a 350 RI detector (Varian, Palo Alto, CA, USA) coupled to the HPLC system. Citric and malic acids were analysed by HPLC-UV at 210 nm using a Rezex™ ROA-Organic Acid H+ (8%) column (150 × 7.8 mm; Phenomenex). The mobile phase consisted of an isocratic gradient of 100% 1 mM H_2SO_4 and the flow rate was 0.5 mL min^{-1}. Total sugar and total acid content were calculated from concentrations of individual compounds as fructose + glucose + sucrose and citric acid + malic acid, respectively. Ratios of contents in citric to malic acid and total sugars to total acids were also calculated. In addition, total sweetness index (tsi) was determined according to Beckles (2012), using the formula tsi = (1.50 × [fructose]) + (0.76 × [glucose]) + (1.00 × [sucrose]).

2.2.4. *Vitamin C*

Content of vitamin C was evaluated from liquid extract preserved with 3% metaphosphoric acid (1:1, v/v). Detection and quantification of vitamin C was performed by HPLC-UV at 254 nm using the 1220 Infinity LC System (Agilent Technologies) and a Brisa “LC^{2}” C18 column (3 µm; 150 × 4.6 mm; Teknokroma, Barcelona, Spain), as the summation of ascorbic and dehydroascorbic acids, following the method described in Chebrolu, Jayaprakasha, Yoo, Jifon, and Patil (2012).

2.2.5. *β-carotene*

β-carotene was extracted using 0.03 g (for pepper and tomato) and 0.1 g (for eggplant) of freeze-dried powder in ethanol:hexane 4:3 (v/v), in a shaker at 200 rpm for 1 h, keeping the samples in the dark. The hexane phase was subsequently separated, and β-carotene was quantified from absorbance values of this fraction measured at 452 nm and

Table 1
Fruit composition traits evaluated in the pepper, tomato and eggplant varieties, abbreviations used and units in which they are expressed.

Fruit composition trait	Abbreviation	Units
Dry matter	dm	g kg^{-1} fw[1]
Soluble solids content	ssc	%
Fruit crude protein content	prot	g kg^{-1} fw
Citric acid content	cit	g kg^{-1} fw
Malic acid content	mal	g kg^{-1} fw
Total acid (citric + malic) content	tacid	g kg^{-1} fw
Citric:malic acid ratio	citmalr	–
Fructose content	fru	g kg^{-1} fw
Glucose content	glu	g kg^{-1} fw
Sucrose content	suc	g kg^{-1} fw
Total sugar (fructose + glucose + sucrose) content	tsug	g kg^{-1} fw
Total sweetness index	tsi	–
Total sugars:total acids ratio	tsugtacidr	–
Vitamin C (ascorbic + dehydroascorbic acid) content	vitc	g kg^{-1} fw
β-carotene content	bcar	mg kg^{-1} fw
Total phenolics content	tpc	g GAE[2] kg^{-1} fw
Total antioxidant activity	taa	mmol TE[3] kg^{-1} fw
Chlorogenic acid	cga	mg kg^{-1} fw
Caffeic acid	caf	mg kg^{-1} fw
Coumaric acid	coum	mg kg^{-1} fw
Ferulic acid	fer	mg kg^{-1} fw
Rutin	rut	mg kg^{-1} fw
Myricetin	myr	mg kg^{-1} fw
Quercetin	quer	mg kg^{-1} fw
Luteolin	lut	mg kg^{-1} fw
Naringenin chalcone	chal	mg kg^{-1} fw
Kaempferol	kaemp	mg kg^{-1} fw
Apigenin	api	mg kg^{-1} fw
Minerals (potassium, phosphorus, calcium, magnesium, sodium, iron, copper, zinc)	K, P, Ca, Mg, Na, Fe, Cu, Zn	mg kg^{-1} fw

[1] fw: fresh weight.
[2] GAE: gallic acid equivalents.
[3] TE: trolox equivalents.

510 nm using a 'UviLine 9400′ UV–VIS spectrophotometer (Schott Instruments, Mainz, Germany) (Zscheile & Porter, 1947).

2.2.6. Phenolic compounds

Standards of the major free phenolic compounds (Sigma-Aldrich) in fruits of pepper, tomato and eggplant, according to literature (García-Salas et al., 2014; Lemos et al., 2019; Slimestad et al., 2008), were used for their identification and quantification in our collection. Compounds analysed are listed in Table 1. Phenolics were extracted using 0.1 g of freeze-dried homogenate, as described in Plazas et al. (2014). One aliquot of this extract was separated to carry out a hydrolysis by adding 3 M HCl (2:1, v/v) for 1 h at 95 °C, in order to free the aglycones (i.e., phenolic skeleton) from their attached sugar chain(s) in flavonoids. Samples were then analysed in the 1220 Infinity LC System (Agilent Technologies) using a Brisa "LC^2" C18 column (3 µm; 150 × 4.6 mm; Teknokroma). Two gradient elution programs were used for analysis of phenolic acids (EP1) and aglycones (EP2), as described in Guijarro-Real et al. (2019). The same mobile phase, consisting of solvent A, 0.1% formic acid in ultrapure water, and solvent B, methanol, was used for both elution programs. Peaks were detected at a fixed wavelength of 320 nm (EP1) and 360 nm (EP2). A tentative identification and quantification of the compounds was conducted by overlapping the retention times of the sample peaks with those of the standards and with data from bibliography. Only compound peaks that exceeded the detection limit (LOD), given by a signal to noise ratio of 3:1 (International Conference on Harmonization, 2014), were considered for quantification. Due to overlapping signal in the EP2 of the major flavonol (quercetin) and flavanone (naringenin) in tomato samples, the standards of the most common quercetin glycoside in tomato rutin (quercetin-3-O-rutinoside), and naringenin chalcone (Sigma-Aldrich) were used to quantify those compounds in the three crops, in addition to those already mentioned, using the EP1 elution program. Thus, tomato samples were not subjected to hydrolysis.

2.2.7. Total phenolics and total antioxidant activity

Total phenolics were extracted using 0.125 g of freeze-dried powder and spectrophotometrically determined according to the Folin-Ciocalteu procedure (Singleton & Rossi, 1965), as indicated in Plazas et al. (2014). Gallic acid was used as standard reference (Sigma-Aldrich).

Total antioxidant activity was evaluated using the colourimetric assay of DPPH• (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging capacity, according to Brand-Williams, Cuvelier, and Berset (1995), with slight modifications. Subsamples of 0.150 g freeze-dried powder were incubated in a shaker with 5 mL of methanol:hydrochloric acid (99:1, v/v) in darkness for 1 h. Subsequently, 0.1 mL of diluted extract with methanol (1:10, v/v) was added to 3.9 mL DPPH• solution (0.025 g L^{-1}) and incubated in darkness for 1 h. Total antioxidant activity was determined from absorbance values of the solution at 515 nm, and using the antioxidant Trolox (Scharlab S.L., Barcelona, Spain) as standard.

2.2.8. Minerals

Extraction of the mineral fraction was performed on 2 g of oven-dried powder, as described in Raigón et al. (2010). Subsequently, content of the minerals (K, P, Ca, Mg, Na, Fe, Cu, Zn) was determined following the MAPA (1994) procedures.

2.3. Data analysis

For each species, the average and its standard error, range and coefficient of variation was calculated for all traits. Data were subjected to analysis of variance using species as factor, and to Student-Newman-Keuls post-hoc multiple range test at $p < 0.05$ for assessing significant differences among species means. Data sets of sucrose, vitamin C, β-carotene and chlorogenic acid content were log-transformed due to wide ranges of values among species and association of means and standard deviation values (Bartlett, 1947). In addition, differences among species for traits that did not have a normal distribution were evaluated using the Kruskal-Wallis non-parametric test (Sheskin, 2020). The relative abundance of the different compounds with respect to the total amount of metabolites within the same category (sugars, acids, antioxidants and minerals) was calculated using average contents for each of the three species. For total antioxidant value, the sum of contents in individual compounds contributing to it (i.e., vitamin C, β-carotene, individual phenolic acids and flavonoids) was considered. Principal components analysis (PCA) was performed using pairwise Euclidean distances among accession means for all the traits. Prediction ellipses for each species with a 95% level of confidence were added to the PCA score plot. A heatmap was constructed in order to cluster the accessions based on fruit composition profile. The software ClustVis was used for that purpose (Metsalu & Vilo, 2015). Original values were ln (x + 1)-transformed, unit variance scaling was applied to all traits and both accessions and traits were clustered using correlation distance and average linkage. The compounds unable to be quantified by HPLC, being below detection limit, were considered in data analysis as 0.

3. Results

3.1. Differences among species for fruit composition profile

The analysis of variance revealed significant differences among species for all traits evaluated, except for total sugars to total acids ratio. In this respect, the three species were significantly different from each other for average contents in dry matter, crude protein, fructose, citric and malic acid, citric to malic acid ratio, vitamin C, caffeic acid, rutin, Mg, Fe and Cu (Tables 2, 3 and 4). Regarding traits related to primary

Table 2
Mean ± standard error (SE), range and coefficient of variation (CV) for species of proximate traits and traits related to primary metabolism analysed in the collection. Species means with different letters are significantly different at $p < 0.05$. The full name of each trait abbreviation in the first column can be found in Table 1.

Traits	Pepper			Tomato			Eggplant		
	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range
dm (g kg^{-1} fw)	123.0^{c} ± 28.1	22.9	76.2–159.1	54.5^{a} ± 8.5	15.7	40.7–66.1	99.3^{b} ± 29.8	30.0	63.3–157.2
prot (g kg^{-1} fw)	11.3^{b} ± 3.4	30.6	6.5–17.0	4.0^{a} ± 0.8	20.0	2.8–5.7	14.9^{c} ± 3.7	24.7	8.1–20.8
ssc (%)	11.0^{b} ± 3.1	27.9	5.8–17.1	5.7^{a} ± 1.4	24.1	4.3–9.2	6.0^{a} ± 1.0	17.4	4.6–8.1
fru (g kg^{-1} fw)	35.5^{c} ± 10.1	28.4	16.0–48.0	18.9^{b} ± 2.8	14.7	15.3–23.5	12.1^{a} ± 3.1	25.4	8.5–17.6
glu (g kg^{-1} fw)	30.4^{b} ± 9.5	31.0	16.6–50.8	16.3^{a} ± 3.5	21.4	12.2–22.3	15.8^{a} ± 2.4	15.4	10.2–18.4
suc (g kg^{-1} fw)	1.2^{ab} ± 1.3	106.9	0.0–3.3	0.1^{a} ± 0.2	229.0	0.0–0.7	3.9^{b} ± 4.1	104.7	0.6–14.7
tsug (g kg^{-1} fw)	67.2^{b} ± 18.3	27.3	35.8–95.2	35.2^{a} ± 6.0	17.0	28.1–45.9	31.9^{a} ± 8.3	25.9	19.5–50.3
tsi	77.6^{b} ± 21.1	27.2	39.8–105.0	40.7^{a} ± 6.5	16.0	32.9–52.3	34.1^{a} ± 9.3	27.2	21.3–54.8
cit (g kg^{-1} fw)	5.4^{c} ± 1.7	32.3	2.8–7.7	3.6^{b} ± 0.9	25.1	2.5–5.4	0.8^{a} ± 0.3	39.9	0.3–1.0
mal (g kg^{-1} fw)	1.9^{b} ± 0.6	30.9	0.7–2.8	1.0^{a} ± 0.2	21.2	0.6–1.4	3.6^{c} ± 1.2	32.9	2.3–6.3
tacid (g kg^{-1} fw)	7.3^{b} ± 2.2	30.5	3.5–10.3	4.6^{a} ± 1.0	21.8	3.4–6.7	4.4^{a} ± 1.4	32.5	2.6–7.5
citmalr	2.9^{b} ± 0.7	23.4	2.0–4.0	3.8^{c} ± 0.8	21.9	2.0–4.6	0.2^{a} ± 0.1	34.1	0.1–0.4
tsugtacidr	9.7 ± 2.7	27.2	5.8–14.0	7.9 ± 1.8	23.1	5.8–11.6	7.6 ± 1.6	21.0	5.5–9.9

Table 3
Mean ± standard error (SE), range and coefficient of variation (CV) for species of traits related to secondary metabolism (antioxidants) analysed in the collection. Species means with different letters are significantly different at $p < 0.05$. The full name of each trait abbreviation in the first column can be found in Table 1.

Traits	Pepper			Tomato			Eggplant		
	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range
vitc (g kg^{-1} fw)	2.36^{c} ± 0.66	27.8	1.56–3.75	0.27^{b} ± 0.05	18.6	0.20–0.37	0.05^{a} ± 0.01	22.8	0.03–0.06
bcar (mg kg^{-1} fw)	39.15^{b} ± 16.93	43.2	6.82–63.44	1.60^{a} ± 1.04	64.8	0.66–3.77	0.48^{a} ± 0.52	107.3	0.01–1.38
cga (mg kg^{-1} fw)	15.8^{a} ± 18.6	117.8	6.0–67.5	20.3^{a} ± 14.8	73.1	8.1–56.0	1,813.9^{b} ± 580.6	32.0	1,278.9–2,956.2
caf (mg kg^{-1} fw)	6.99^{a} ± 2.78	39.7	0.88–10.51	BDL[d]			34.55^{b} ± 12.55	36.3	16.26–51.84
fer (mg kg^{-1} fw)	4.08 ± 3.63	89.1	0.00–9.50	BDL			BDL		
coum (mg kg^{-1} fw)	BDL			BDL			BDL		
rut (mg kg^{-1} fw)	15.4^{a} ± 9.3	60.3	0.0–24.3	41.2^{b} ± 20.9	50.9	22.5–80.2	BDL		
myr (mg kg^{-1} fw)	0.93 ± 1.01	107.9	0.00–3.08	BDL			BDL		
quer (mg kg^{-1} fw)	384.5 ± 158.0	41.1	167.6–707.6	BDL			BDL		
lut (mg kg^{-1} fw)	17.7 ± 8.0	45.3	7.1–32.9	BDL			BDL		
chal (mg kg^{-1} fw)	BDL			25.1 ± 23.6	93.9	0.0–70.6	BDL		
kaemp (mg kg^{-1} fw)	3.05 ± 1.11	36.3	0.98–4.91	BDL			BDL		
api (mg kg^{-1} fw)	3.36 ± 1.42	42.1	0.60–4.85	BDL			BDL		
tpc (g GAE kg^{-1} fw)	1.11^{b} ± 0.52	46.9	0.62–2.41	0.38^{a} ± 0.09	23.8	0.22–0.49	2.70^{b} ± 0.72	26.7	1.92–3.76
taa (mmol TE kg^{-1} fw)	36.2^{b} ± 8.1	22.4	23.0–47.4	21.4^{a} ± 3.6	17.0	15.7–26.7	37.2^{b} ± 7.5	20.1	22.5–51.2

[d] BDL: below detection limit.

Table 4
Mean ± standard error (SE), range and coefficient of variation (CV) for species of minerals analysed in the collection. Species means with different letters are significantly different at $p < 0.05$. The full name of each trait abbreviation in the first column can be found in Table 1.

Traits	Pepper			Tomato			Eggplant		
	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range	Mean ± SE	CV (%)	Range
K (mg kg^{-1} fw)	935.0^{a} ± 266.8	28.5	615.8–1,364.4	900.1^{a} ± 128.0	14.2	683.6–1,176.9	3,266.4^{b} ± 567.1	17.4	2,421.4–4,465.5
P (mg kg^{-1} fw)	408.7^{b} ± 92.4	22.6	311.0–583.9	158.9^{a} ± 24.3	15.3	124.4–211.6	388.9^{b} ± 77.9	20.0	297.2–534.3
Ca (mg kg^{-1} fw)	117.4^{b} ± 31.6	26.9	74.4–167.3	70.8^{a} ± 17.8	25.1	59.7–113.5	102.9^{b} ± 23.1	22.4	81.0–145.5
Mg (mg kg^{-1} fw)	126.3^{b} ± 34.0	26.9	78.5–189.1	64.5^{a} ± 15.7	24.3	40.0–95.5	179.3^{c} ± 46.6	26.0	106.8–249.7
Na (mg kg^{-1} fw)	31.0^{ab} ± 13.0	41.9	14.2–53.0	20.4^{a} ± 3.8	18.8	14.4–26.7	41.0^{b} ± 15.2	37.0	24.0–67.2
Fe (mg kg^{-1} fw)	5.77^{c} ± 1.75	30.3	2.91–7.95	1.81^{a} ± 0.51	28.3	1.11–2.39	3.53^{b} ± 1.11	31.3	2.07–5.25
Cu (mg kg^{-1} fw)	0.86^{b} ± 0.37	42.9	0.35–1.40	0.39^{a} ± 0.10	26.6	0.23–0.58	1.21^{c} ± 0.31	26.0	0.83–1.77
Zn (mg kg^{-1} fw)	2.71^{b} ± 0.77	28.4	1.39–3.93	1.34^{a} ± 0.29	21.4	0.81–1.82	3.07^{b} ± 0.81	26.3	1.81–4.77

metabolism, pepper had the highest average content in fructose by 1.9-fold and 2.9-fold compared to tomato and eggplant, respectively. The same happened for citric acid content, which was 1.5-fold and 6.6-fold greater, respectively. In addition, pepper had around 2-fold higher average content in soluble solids, glucose, total sugars, total acids and total sweetness index, compared to tomato and eggplant (Table 2). The sugar profile was very similar between pepper and tomato, with fructose content contributing around 50% to the total sugars, and sucrose representing more than 2% (Fig. 2). Although sucrose was the less abundant sugar for the three species, average levels of it in eggplant were more than 3-fold and 30-fold higher than those of pepper and tomato, respectively (Table 2). Thus, sucrose contributed to the eggplant sweetness profile to a larger extent (12%), at the expense of a reduced percentage in fructose content (38%) (Fig. 2). Eggplant also stood out for its higher content in crude protein and malic acid, which were, respectively, 1.3-fold and 1.9-fold higher than in pepper; and 3.7-fold higher than in tomato, in both cases (Table 2). Therefore, malic was the acid contributing the most to the total acid content in eggplant, accounting for 82%; whereas the opposite was found for pepper and tomato, in which citric acid accounted for 74% and 79%, respectively (Fig. 2).

With respect to secondary metabolites, no significant differences were found between pepper and eggplant for average total antioxidant activity, and both values were 1.7-fold higher than for tomato. Both vitamin C and β-carotene contents had mean values significantly higher,

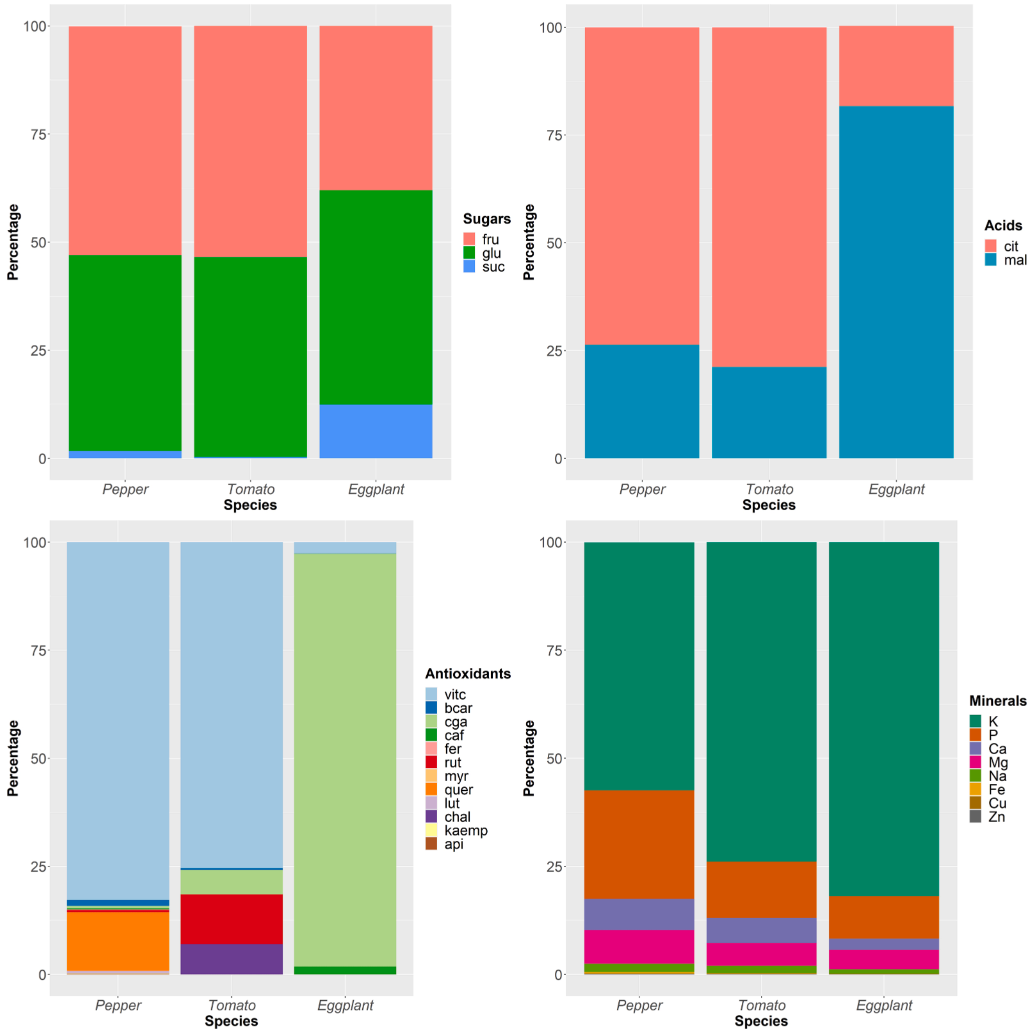

Fig. 2. Stacked bar plots showing relative abundances (%) of average contents in different sugar, acid, antioxidant and mineral compounds over the total amount of each category present in each of the three species evaluated (pepper, tomato and eggplant). The names of the compounds are shown as the abbreviation used in the present work and listed in Table 1.

by a large extent, in pepper than in tomato or eggplant (Table 3). Among the antioxidant compounds evaluated, vitamin C represented the highest percentage in pepper (83%) and tomato (75%), while in eggplant, it represented more than 3% (Fig. 2). Although no significant differences between pepper and eggplant were found for total phenolics content, diverse profiles of individual phenolic compounds were identified among the three species. Eggplant showed an outstandingly high average content of chlorogenic acid (1,813.9 mg kg^{-1}, expressed on a fresh weight basis (fw)), contributing 96% to the total content in antioxidants for that species; while pepper and tomato accumulated more than 25.0 mg kg^{-1} fw of chlorogenic acid. The flavonoid quercetin was the most important phenolic compound in pepper (384.5 mg kg^{-1} fw on average), which contributed 14% to the content of total antioxidants, followed by luteolin (17.7 mg kg^{-1} fw on average). Rutin constituted the most relevant phenolic compound for tomato (41.2 mg kg^{-1} fw on average), which accounted for 12% of the total content of antioxidants (Table 3, Fig. 2).

Regarding mineral composition, eggplant stood out for its high average content in K (3,266.4 mg kg^{-1} fw), which was around 3.5-fold higher than in both pepper and tomato. Pepper displayed the highest average content in Fe (5.77 mg kg^{-1} fw), which was 1.6 and 3.2-fold higher than in eggplant and tomato, respectively. Tomato, in general, had the lowest concentrations of minerals among the three species (Table 4). Despite those differences, the relative contribution of each mineral compound to the total content of those analysed was similar for the three species, although proportions changed slightly among them. Thus, K represented the highest percentage of the total (between 57% in pepper and 82% in eggplant); whereas Fe, Cu and Zn represented more than 1% of the total, for the three species (Fig. 2).

Considerable variation was found among the accessions regarding primary and secondary metabolism traits and minerals (Tables 2, 3, and 4). In this way, the coefficient of variation (CV) exceeded 100% in the case of sucrose for the three species, and also for chlorogenic acid and myricetin for pepper. Apart from sucrose, the highest CV in tomato was found for the content of naringenin chalcone (93.9%), and in eggplant, for total carotenoid content (81.4%). On the other side, the traits that displayed the lowest CV were total antioxidant activity and P content for pepper (around 22%), content in K and fructose for tomato (around 14%), and glucose and soluble solids contents for eggplant (15.4% and 17.4%, respectively) (Tables 2, 3, and 4). Individual data for each variety of the collection and the differences among them within species are included as Supplementary file S1.

3.2. *Principal components and cluster analyses*

The first two principal components (PCs) of the PCA explained 75.1% of the total variation observed, with PC1 and PC2 accounting for 41.0% and 34.1% of the total variation, respectively (Fig. 3A, 3B). When

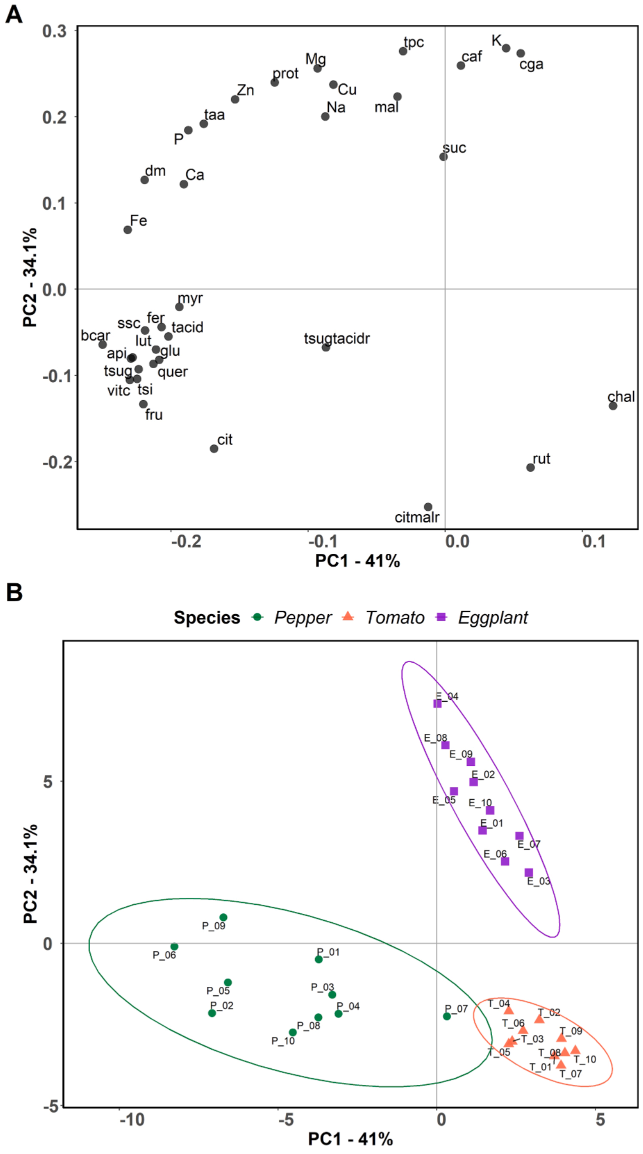

Fig. 3. PCA loading plot (A) and score plot (B) evaluated in the present study based on the two first principal components of PCA. First and second components account for 41.0% and 34.1% of the total variation, respectively. The accessions are represented by different symbols and colour according to the species: green circle for pepper, orange triangle for tomato and purple square for eggplant. Ellipses grouped the accessions of each species with a 95% confidence level. The full name of each trait abbreviation can be found in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

considering traits with correlations above 0.2 with PC1 or PC2 it was found that dry matter, contents in fructose, glucose, total sugars and acids, β-carotene, vitamin C, flavonoids (except rutin, myricetin and naringenin chalcone), and Fe, were negatively correlated to PC1. Besides, contents in protein, malic acid, total phenolics, phenolic acids (except ferulic acid), and minerals (except P, Ca and Fe), were positively correlated to PC2, while citric:malic acid ratio and rutin were negatively correlated to PC2 (Fig. 3A).

The PCA clearly separated the thirty varieties evaluated into three groups that matched the corresponding species (Fig. 3B). All eggplant varieties clustered together in the upper right quadrant of the PCA score plot (Fig. 3B), corresponding to positive values for both PC1 and PC2; all tomato varieties were grouped together in the lower right quadrant, showing positive values for PC1 but negative for PC2; finally, most of the pepper varieties plotted in the lower left quadrant, with negative values for both PC1 and PC2, except for one accession that showed positive values for PC1 and one accession that showed low positive values for PC2 (Fig. 3B). The more widespread distribution of pepper accessions, as opposed to the narrower distribution of the tomato and eggplant accessions, indicated a larger variability; while the lowest variation was found within tomato. Confidence ellipses of pepper and tomato overlapped, although to a very small extent, due to the pepper variety P_07, whose composition profile was more similar to the one of tomato (Fig. 3B).

The multivariate cluster heatmap in Fig. 4 revealed three major clusters for the varieties, each of which corresponded to each of the species studied, indicating considerable differences in the composition profile of fruits of pepper, tomato and eggplant. In addition, the analysis separated the compounds and parameters analysed in two large clusters. The upper cluster grouped all the mineral compounds together and the phenolic acids, except ferulic acid. On the other side, all the flavonoids appeared in the lower cluster, along with vitamin C, β-carotene, and all the parameters related to sweetness, acidity and the balance between them, except sucrose and malic acid (Fig. 4). Within the diversity found for each species, eggplant variety E_05 showed the highest average content in sucrose and malic acid, while E_04 had the best profile in total phenolics and antioxidant activity, phenolic acids (chlorogenic and caffeic) and minerals. In addition, pepper varieties P_06 and P_09 stood out for having the greatest content in myricetin, and high values for mineral composition; P_04 showed the best content in major flavonoids in pepper: quercetin, luteolin and apigenin; and P_10 and P_02 accumulated more sugars in their fruits, having the best sweetness profile, as well as an outstanding content in vitamin C. Lastly, the tomato variety T_07 had the highest content in flavonoids naringenin chalcone and rutin (Fig. 4).

3.3. Contribution to RDA/AI

Based on data of the nutrients included in the daily Recommended Dietary Allowance (RDA) and the Adequate Intake (AI) reports (Institute of Medicine, 2006), and using average data for species, consuming daily 100 g portion of red sweet pepper, tomato or eggplant, could contribute to the RDA/AI in a low (<3%) or moderate (3–6%) level for most of the compounds evaluated (Table 5). Nevertheless, a 100 g portion of pepper largely exceeded the daily RDA for vitamin C, with an outstanding average contribution of 262% and 314% for males and females, respectively. In addition, there is a relevant (>6%) contribution to the daily RDA of 100 g of pepper and eggplant for Cu (9.6% and 13.4%, on average, respectively). Pepper also stood out for its mean contribution to daily RDA for Fe (7.2% for adult males, and females above 51 years old). Tomato, in a 100 g portion basis, had lower percentages of contribution to the RDA than pepper and eggplant in all cases; however, among the compounds evaluated, tomato had an average contribution to the vitamin C daily RDA of 30% and 36% for males and females, respectively (Table 5).

Regarding relative ranges of variation of 100 g portion contributions to daily RDA/AI, the largest values for pepper and tomato were found for their contributions to the Cu daily RDA (4-fold and 2.5-fold) and for eggplant, to the Na daily AI (2.8 to 2.9-fold). On the other hand, the lowest values of the same parameter for eggplant and pepper were observed for their contribution to the P daily RDA (1.8 and 1.9-fold), and in the case of tomato, to the daily RDA for carbohydrates (estimated as total sugars) (1.6-fold) (Table 5).

4. Discussion

The present study provides a thorough comparison of the nutritional and organoleptic value of three major vegetables from the highly important family *Solanaceae*. The experiment was performed under the same environmental conditions, which is of considerable interest due to

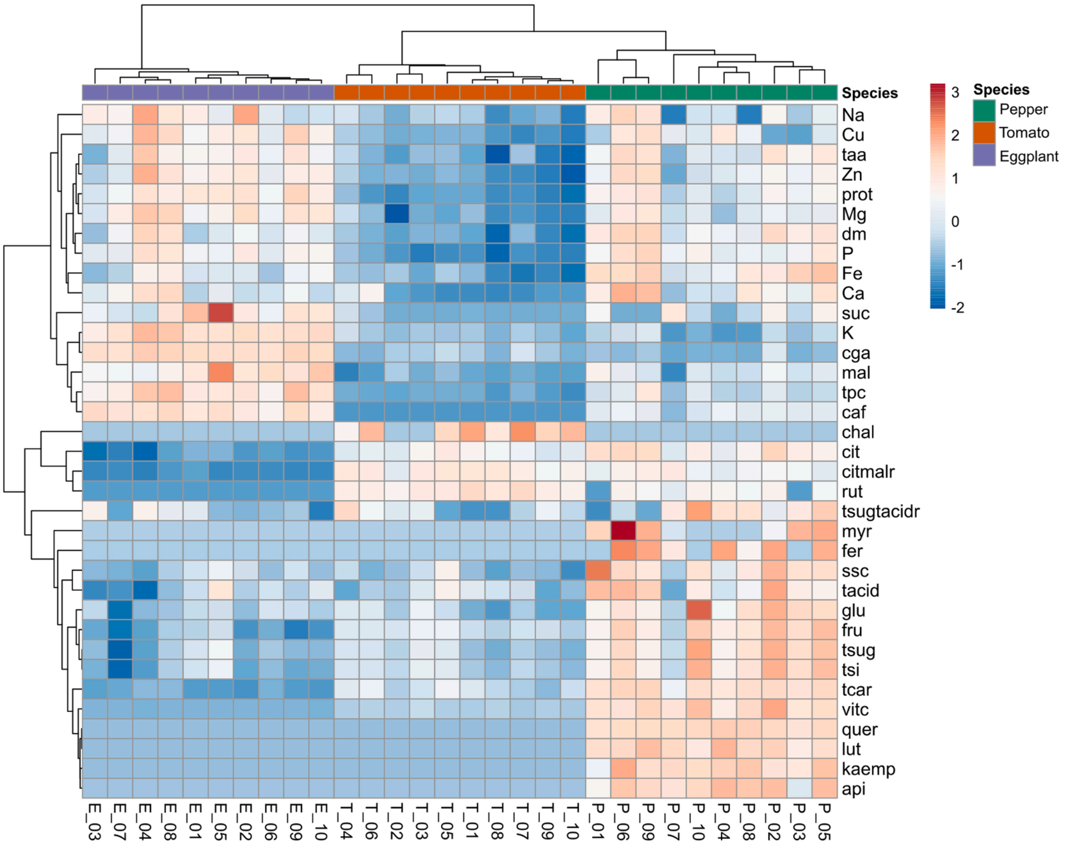

Fig. 4. Heatmap representing the hierarchical clustering of the 30 accessions studied based on their fruit composition profiles. Columns represent the accessions and rows represent the traits evaluated. Unit variance scaling was applied to rows. Both rows and columns are clustered using correlation distance and average linkage. The scale of the colour intensity is shown in the top right corner and it represents a proportional value of the compound content. The full name of each trait abbreviation can be found in Table 1.

Table 5
Contribution of 100 g of the pepper, tomato and eggplant fruits to daily Recommended Dietary Allowances (RDA) or Adequate Intake (AI) (Institute of Medicine, 2006) for protein, carbohydrates (estimated as total sugars), vitamin C and all minerals studied, considering average values and range (in parentheses) per species of those traits. RDA or AI considered corresponded to adult males and females ≥ 18 years old (yo).

Nutrient	Daily RDA/AI		Contribution of 100 g to daily RDA/AI (%)					
			Pepper		Tomato		Eggplant	
	Male	Female	Male	Female	Male	Female	Male	Female
Protein (g[a])	56	46	2.0 (1.2–3.0)	2.4 (1.4–3.7)	0.7 (0.5–1.0)	0.9 (0.6–1.2)	2.7 (1.4–3.7)	3.2 (1.8–4.5)
Carbohydrates (g)	130	130	5.2 (2.8–7.3)	5.2 (2.8–7.3)	2.7 (2.2–3.5)	2.7 (2.1–3.5)	2.5 (1.5–3.9)	2.5 (1.5–3.9)
Vitamin C (g)	0.090	0.075	262 (173–417)	314 (208–500)	30.0 (22.2–41.1)	36.0 (26.7–49.3)	5.6 (3.8–7.0)	6.7 (4.5–8.4)
Ca (mg)	1000 1200 (≥51 yo)	1000 1200 (≥51 yo)	1.2 (0.7–1.7) 1.0 (0.6–1.4)	1.2 (0.7–1.7) 1.0 (0.6–1.4)	0.7 (0.6–1.1) 0.6 (0.5–1.0)	0.7 (0.6–1.1) 0.6 (0.5–1.0)	1.0 (0.8–1.5) 0.9 (0.7–1.2)	1.0 (0.8–1.5) 0.9 (0.7–1.2)
Cu (mg)	0.9	0.9	9.6 (3.9–15.6)	9.6 (3.9–15.6)	4.3 (2.6–6.4)	4.3 (2.6–6.4)	13.4 (9.2–19.7)	13.4 (9.2–19.7)
Fe (mg)	8	8 18 (19–50 yo)	7.2 (3.6–9.9)	7.2 (3.6–9.9) 3.2 (1.6–4.4)	2.3 (1.4–3.0)	2.3 (1.4–3.0) 1.0 (0.6–1.3)	4.4 (2.6–6.6)	4.4 (2.6–6.6) 2.0 (1.2–2.9)
Mg (mg)	400 (19–30 yo) 420 (≥31 yo)	310 (19–30 yo) 320 (≥31 yo)	3.2 (2.0–4.7) 3.0 (1.9–4.5)	4.1 (2.5–6.1) 3.9 (2.5–5.9)	1.6 (1.0–2.4) 1.5 (1.0–2.3)	2.1 (1.3–3.1) 2.0 (1.3–3.0)	4.5 (2.7–6.2) 4.3 (2.5–5.6)	5.8 (3.5–8.1) 5.6 (3.3–7.8)
P (mg)	700	700	5.8 (4.4–8.3)	5.8 (4.4–8.3)	2.3 (1.8–3.0)	2.3 (1.8–3.0)	5.6 (4.3–7.6)	5.6 (4.3–7.6)
K (mg)	4700	4700	2.0 (1.3–2.9)	2.0 (1.3–2.9)	1.9 (1.5–2.5)	1.9 (1.5–2.5)	6.9 (5.2–9.5)	6.9 (5.2–9.5)
Na (mg)	1500 1300 (51–70 yo) 1200 (≥70 yo)	1500 1300 (51–70 yo) 1200 (≥70 yo)	0.21 (0.09–0.35) 0.24 (0.11–0.41) 0.26 (0.12–0.44)	0.21 (0.09–0.35) 0.24 (0.11–0.41) 0.26 (0.12–0.44)	0.14 (0.10–0.18) 0.16 (0.11–0.21) 0.17 (0.12–0.22)	0.14 (0.10–0.18) 0.16 (0.11–0.21) 0.17 (0.12–0.22)	0.27 (0.16–0.45) 0.32 (0.18–0.52) 0.34 (0.20–0.56)	0.27 (0.16–0.45) 0.32 (0.18–0.52) 0.34 (0.20–0.56)
Zn (mg)	11	8	2.5 (1.3–3.6)	3.4 (1.7–4.9)	1.2 (0.7–1.7)	1.7 (1.0–2.3)	2.8 (1.7–4.3)	3.8 (2.3–6.0)

[a] Based on g protein per kg of body weight for the Reference Body Weight (70 kg for adult males and 57 kg for adult females) (Institute of Medicine, 2006).

the polygenic control of fruit composition traits and the strong influence of the environmental conditions on the final phenotype (Cebolla-Cornejo et al., 2011; Figàs et al., 2018; Stommel et al., 2015; Tripodi et al., 2018). Results showed considerably different quality profiles among the three species. This is in agreement with studies in comparative genomics that have already reported the large diversity within the *Solanaceae* family, more specifically within the genus *Solanum* (Arnoux, Fraïsse, & Sauvage, 2021).

Regarding all traits except phenolic compounds, compared to USDA National Nutrient Database (U.S. Department of Agriculture, 2021) and data from other works, our results showed similar or higher average and higher maximum values for most of the traits evaluated in pepper (Chassy et al., 2006; Eggink et al., 2012; Fratianni et al., 2020; Guilherme, Reboredo, Guerra, Ressurreição, & Alvarenga, 2020; Lo Scalzo, Campanelli, Paolo, Fibiani, & Bianchi, 2020; Mennella et al., 2018), tomato (Casals et al., 2019; Cebolla-Cornejo et al., 2011; Chassy et al., 2006; Hallmann, 2012; Martí et al., 2018; Martínez-Valverde, Periago, Chesson, & Provan, 2002), and eggplant (Ayaz et al., 2015; Hanson et al., 2006; Luthria et al., 2010; Raigón et al., 2010; San José et al., 2013). Furthermore, ranges of values between our experiment and the others overlapped to a greater or lesser extent; e.g., β-carotene content values for pepper in Mennella et al. (2018), dry matter results for tomato in Martínez-Valverde et al. (2002) or Mg contents for eggplant in Ayaz et al. (2015). Contrarily, higher average contents were found for a few compounds in other works than ours, including total phenolics and K for pepper in the USDA National Nutrient Database, and K in Guilherme et al. (2020); protein, β-carotene, total phenolics and all mineral compounds for tomato in the USDA National Nutrient Database, all minerals except K in Fernández-Ruiz, Olives, Cámara, Sánchez-Mata, and Torija (2011), and total phenolics in Hallmann (2012); finally, for eggplant, vitamin C in Ayaz et al. (2015), and Na in Raigón et al. (2010).

Regarding phenolic compounds, a wide range with considerable variation in concentration have been described in several cultivars of pepper (Chassy et al., 2006; Fratianni et al., 2020; Lemos et al., 2019; Ribes-Moya et al., 2020), tomato (Chassy et al., 2006; Hallmann, 2012; Martí et al., 2018; Slimestad et al., 2008) and eggplant (García-Salas et al., 2014; Singh et al., 2009; Whitaker & Stommel, 2003), especially for the former. Based on the previous literature, the most abundant compounds in each of the three species were selected to analyse their concentration in fruits of our collection. Thus, more compounds were identified and quantified in pepper (9 out of 11) than in tomato (3 out of 11) and eggplant (2 out of 11). The widest range of variation among studies was found for pepper. Although lower average values for some compounds were found in our study compared to others, ranges of values overlapped to a large extent; except for luteolin and myricetin contents in Ribes-Moya et al. (2020), chlorogenic acid and myricetin in Fratianni et al. (2020) and kaempferol in Chassy et al. (2006). For tomato, higher average and large but overlapping ranges were observed for chlorogenic acid and rutin as compared to the data obtained by Hallmann (2012) and Martí et al. (2018). In addition, similar range of values to those observed by Slimestad et al. (2008) was found for naringenin chalcone in tomato. Contrarily, trace amounts of caffeic, *p*-coumaric and ferulic acid were detected in tomato by Martí et al. (2018), while none exceeded the detection limit in our study.

It should be noted that, in the literature mentioned, only cultivated varieties with similar way of consumption to those used by us, and in which fruits were analysed raw at the same ripening stage as in our experiment, were taken into account. The differences observed among studies may be due to the cultivars selected, analytical methods used and the different environment and cultivation practices under which plants were grown. Furthermore, more differences and larger ranges of variation among studies were found for secondary metabolites compared to the primary metabolites and mineral contents, which may be the result of domestication (Pott et al., 2019). Those data confirm the strong environmental influence on the synthesis and accumulation of compounds related to nutritional and organoleptic quality, especially for secondary metabolites, since their synthesis is usually triggered by a stressful condition (Yang et al., 2018).

Based on our results, a selection of varieties with better profiles could be of interest for future breeding programs and for cultivation under organic conditions. Among the varieties evaluated in the present study, the pepper P_10 would represent a good source for improving sweetness and vitamin C content. Besides, P_09 and P_06 showed high nutritional properties for their mineral and carotenoid contents, and total antioxidant activity. P_04 was another variety to consider for improving content in major flavonoids (quercetin, luteolin and apigenin) in pepper. The best tomato varieties to consider for future breeding programs were T_04, for its content in minerals, protein and sugar-acid balance, T_05 for its content in carotenoids and T_07 for its content in major flavonoids. In the case of eggplant varieties, E_04 and E_08 would represent the best source for improving mineral content and antioxidant properties in this species. In addition, these varieties were among the best regarding sugar-acid balance. On the other hand, E_05 could be a good resource for the improvement of sweetness in general and sucrose content in particular.

4.1. Pepper, tomato and eggplant differences in primary metabolites

In the present study, significant differences among pepper, tomato and eggplant, for sugar and acid profiles were detected, which would contribute to the differences in perception of their taste. Pepper showed the highest average values of total sugars, total sweetness index, and total acid content; while tomato and eggplant showed no significant differences in terms of total sugars and acids. In addition, results revealed that major sugars in fruit for the three species were fructose and glucose, while sucrose accumulation was marginal. Nevertheless, sucrose accumulation in eggplant was significantly higher than in the other two species, representing a higher percentage of total sugars at the expense of fructose. On the other hand, citric was the major organic acid in pepper and tomato, while in eggplant was malic. The same profile of sugars and acids was described for pepper (Lo Scalzo et al., 2020), tomato (Quinet et al., 2019) and eggplant (Ayaz et al., 2015; San José et al., 2013). Although the sugar-acid balance showed no significant differences among the three species, the differences in their sugar and acid profiles would give a more sweet or sour taste to the fruit, since malic acid has twice the acidic potential of citric acid and the sweetness potential of sugars follows this order: fructose > sucrose > glucose (Beckles, 2012).

Our results suggest a similar pattern, among the three species, of the mechanisms involved in the accumulation of sugars in the fruit. The marginal accumulation of sucrose could be explained by the limited activity of the sucrose-phosphate-synthase compared to a significant increase in the invertase activity during fruit ripening (Quinet et al., 2019). In addition, it has been reported that, during tomato fruit ripening, an important part of malic acid is converted to simple sugars via gluconeogenesis (Schouten, Woltering, & Tijskens, 2016). In this way, the higher proportion of sucrose found in eggplant with respect to tomato and pepper in the present study, as well as the predominance of malic over citric acid, might be due to the fact that the eggplant is harvested and consumed at physiological immaturity.

4.2. Pepper, tomato and eggplant differences in secondary metabolites

Considerable differences among the three solanaceous fruits were detected for the profile of secondary metabolites. Unlike for primary metabolites, data of total antioxidant activity are difficult to compare with other reports because of the lack of a standard official procedure (López-Alarcón & Denicola, 2013). In our experiment, no significant differences were found between pepper and eggplant for antioxidant activity and both had higher average values than tomato. In Morales-Soto et al. (2014), who evaluated 44 fruits and vegetables for total antioxidant activity, different profiles, depending on the methodology used, were found. However, pepper and eggplant had higher maximum values than tomato in most of the cases. Interestingly, pepper and eggplant were among the five best fruits and vegetables out of the 44 evaluated by these authors.

Major compounds contributing to the fruit antioxidant activity were considerably different among the three species. In addition, each antioxidant compound would contribute differently to the total antioxidant activity depending on their free radical scavenging capacity. According to Kim and Lee (2004), the ranking of compounds analysed in the present study for their scavenging capacity relative to vitamin C, would be as follows: myricetin > quercetin > luteolin > ferulic acid > naringenin > kaempferol > caffeic acid > vitamin C > apigenin > chlorogenic acid > rutin > carotenoids. Furthermore, some differences in this ranking could be found depending on the antioxidant assay used for the evaluation. For instance, carotenoids are not capable of scavenge the DPPH• (Müller, Fröhlich, & Böhm, 2011), and thus, did not contribute to the total antioxidant activity in this study.

In pepper, the main antioxidant compound of those evaluated was vitamin C, representing 82% of the total content in antioxidants evaluated, followed by the flavonoid quercetin (13%) and β-carotene (1.4%). This is in agreement with other studies (Chassy et al., 2006; Fratianni et al., 2020). Others reported luteolin as the predominant phenolic, ahead of quercetin (Ribes-Moya et al., 2020). In tomato, vitamin C (74%) was also the main antioxidant compound, followed by the flavonoids rutin (quercetin-3-*O*-rutinoside) (11%) and naringenin chalcone (7%). This is in agreement with previous studies (Chassy et al., 2006; Hallmann, 2012; Martí et al., 2018; Slimestad et al., 2008). Eggplant showed a more distinct profile of antioxidant compounds than pepper and tomato. While vitamin C content only represented 3% of the total antioxidants evaluated, chlorogenic acid was identified as the major antioxidant in eggplant (96%), as observed in previous research (Luthria et al., 2010; Whitaker & Stommel, 2003). Fewer characterizations of vitamin C content in eggplant have been carried out compared to pepper and tomato. However, the coefficient of variation for that compound indicated that there is room for improvement in this species. Selecting high-vitamin C varieties in eggplant would not only imply a health benefit related to consumption, but it would also be beneficial for the fruit organoleptic quality, as it may reduce browning, a non-desirable trait for consumers, caused by the oxidation of polyphenols (San José et al., 2013).

A wide range of natural pigments within the group of carotenoids exists among vegetables (Young & Lowe, 2018). Although these compounds are synthesised from the same metabolic pathway, the differential expression of genes associated with enzymes involved in it results in different carotenoids accumulating to a greater or lesser extent in fruits of peppers, tomatoes and eggplants (Barchi et al., 2019; Paran & Van Der Knaap, 2007). We have focused on β-carotene due to its important role in human health. Besides its function as free radical quencher, and thus its protective role against oxidative stress, its role as vitamin A precursor has been widely studied (Fiedor & Burda, 2014). Our results showed a higher content of β-carotene in pepper than in tomato or eggplant by around 40-fold. Results in most of other works showed considerably lower amounts of β-carotene in pepper (Fratianni et al., 2020; Marín, Ferreres, Tomás-Barberán, & Gil, 2004; U.S. Department of Agriculture, 2021), indicating a lower difference with tomato. This may be due to the presence of other yellow-orange carotenoids in pepper, as lutein and zeaxanthin, absent in tomato and eggplant, that had absorption maxima at similar wavelengths, potentially overestimating β-carotene content estimates in our study (Ribes-Moya, Raigón, Moreno-Peris, Fita, & Rodríguez-Burruezo, 2018). Although it would be more accurate to quantify carotenoids by more specific and sensitive methods such as HPLC, using spectrophotometry is a reliable, easy, fast and cost-effective method for comparison among different samples in the same study.

Selecting and breeding for higher content in phenolic compounds, which includes both phenolic acids and flavonoids, is of utmost interest due to the health benefits associated to them (Cory, Passarelli, Szeto, Tamez, & Mattei, 2018; Rodriguez-Mateos, Heiss, Borges, & Crozier, 2014). In the present study, results showed significant differences among the three solanaceous species for total phenolics content in fruits. Thus, eggplant showed the highest average values and the lowest were found for tomato, while pepper had intermediate values. Regarding phenolic acids, chlorogenic acid was detected in the three species, although in eggplant the average content was around 100-fold higher than in the others; caffeic acid was quantified in pepper and eggplant; ferulic acid only in pepper; and *p*-coumaric acid was detected in none of them. In other studies, higher resolution analyses using LC-MS technology identified caffeic acid and *p*-coumaric acid and its derivatives in tomato landraces (Pinela et al., 2019). With respect to flavonoids, most were detected only in pepper fruits: quercetin, luteolin, apigenin, kaempferol and myricetin, in decreasing order of relevance. The detection of a certain amount of rutin (quercetin-3-*O*-glycoside) in peppers indicates that a small proportion of the quantified quercetin (4% on average) would appear as that glycoside. The presence of rutin in pepper has also been reported in other works such as Fratianni et al. (2020). For tomato, there is evidence in literature that most of quercetin content appear as rutin (Slimestad et al., 2008). We were able to detect and quantify rutin as the major flavonoid of those evaluated in tomato, followed by naringenin chalcone. Those results are in agreement with Slimestad et al. (2008) and Martí et al. (2018). Other studies were able to quantify kaempferol and other flavonoids in tomato, although in trace amounts (Chassy et al., 2006; Hallmann, 2012; Pinela et al., 2019). Both rutin and free quercetin have been reported to show health benefits at some extent, reducing risks of neurodegenerative disorders, cancer, atherosclerosis and other cardiovascular diseases (Frutos et al., 2019; Jeong, An, Kwon, Rhee, & Lee, 2009; Kleemann et al., 2011). On the other hand, in the present study, no flavonoids were detected in eggplant fruits. Although some studies have been able to identify and quantify flavonoids in eggplant flesh, those compounds were found in trace amounts, thus most of the studies in this area focused their efforts on identifying isomers and derivatives of chlorogenic and caffeic acid (García-Salas et al., 2014; Singh et al., 2009).

4.3. *Pepper, tomato and eggplant differences in mineral composition*

The present study suggests the same pattern of accumulation of mineral compounds in pepper, tomato and eggplant. In addition, the major mineral compound in the three species was K, followed by P and Ca or Mg. This is in agreement with other works (Ayaz et al., 2015; Fernández-Ruiz et al., 2011; Guilherme et al., 2020; Raigón et al., 2010; U.S. Department of Agriculture, 2021), although individual contents may vary among studies, probably due to their high dependence on the soil composition and minerals availability (Raigón et al., 2010). High variation coefficients were found, mainly among pepper varieties, which facilitate the selection of better genotypes for its cultivation under organic conditions. Although studies have been done to elucidate the genetic control of mineral accumulation in tomato fruit (Capel et al., 2017), detailed analysis of the regulation of fruit mineral contents, as well as their characterization in different populations of pepper, tomato and eggplant, are still lacking.

4.4. *Relevance of pepper, tomato and eggplant on a balanced diet*

According to the contributions of 100 g portion to the daily RDA/AI, pepper, tomato and eggplant are, as most vegetables (Yahia et al., 2019), poor sources of protein, sugars, Na and Ca. Except for Ca, this promotes a healthy diet, since an excess of sugars and salt increases the risks of diseases such as Type II diabetes and hypertension. Furthermore, these three vegetables are rich sources of antioxidant compounds and other minerals. As it is already known (García-Closas et al., 2004; Yahia et al., 2019), pepper and tomato would be two of the best sources for dietary vitamin C intake, making outstanding contributions to the daily RDA

(288% and 33% in average, respectively). In agreement with our results, other studies reported pepper (100 g serving) contributions to the vitamin C RDA over 100% (Howard, Talcott, Brenes, & Villalon, 2000; Wahyuni et al., 2013) with similar ranges of values. In fact, the range of mean values for vitamin C content in the pepper varieties in the present study was higher than the USDA standard reference values for this trait in vegetables such as broccoli and cauliflower, and in fruits such as kiwi and oranges (U.S. Department of Agriculture, 2021). In tomato (100 g serving), we have found higher contribution percentages to the vitamin C RDA in our data compared to other studies (Casiraghi et al., 2013). On the contrary, a serving of tomato in our study showed lower contribution percentages to AI or RDA values for minerals regarding K, P and Mg than in other works (Casiraghi et al., 2013; Hernández Suárez, Rodríguez Rodríguez, & Díaz Romero, 2007; Mohammed et al., 2020). Eggplant, on the other hand, stood out for being the best source of mineral compounds among the three species, specifically for Cu, Mg, K, Na and Zn. Compared with data in Raigón et al. (2008), higher average contribution to the K AI was found herein, while for P RDA the contribution percentages were within the same range. In any case, the complementary profile of fruit composition observed for pepper, tomato and eggplant would make it advisable to combine the consumption of those three vegetables in the diet.

5. Conclusions

The comprehensive characterization of fruit composition profile performed herein provides insight into the different regulation patterns of metabolite accumulation among pepper, tomato and eggplant, which were grown under the same organic cultivation conditions. Results allowed to describe the existing diversity within and among the three species for fruit quality. Given the results, the combination of pepper, tomato and eggplant consumption would constitute an advantageous option for a well-balanced diet due to their complementary nutritional and functional profile. In this way, pepper stood out for its high content in vitamin C, so that a 100 g serving would cover the recommended daily intake of this essential nutrient. Besides being an important source of vitamin C, tomatoes are also rich in the health-promoting flavonoid rutin. Eggplant, on the other side, represented the best source of minerals and phenolic acids, mainly chlorogenic acid, which contributes to its high antioxidant activity. The contribution of a 100 g serving of pepper, tomato and eggplant to the RDA or AI values for several compounds analysed is also provided, which may be of interest for nutrition programs guidance. The wide variability found among the varieties evaluated indicates that it would be inaccurate to assign absolute values when describing the nutritional content of these three vegetables, but that ranges of values should be given instead. In addition, some varieties of pepper, tomato and eggplant were highlighted for its use and conservation due to their higher content in one or more traits analysed. This diversity would provide researchers relevant information for selection of varieties with better nutritional and organoleptic properties as well as for potential utilization in breeding programs.

CRediT authorship contribution statement

Elena Rosa-Martínez: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **María Dolores García-Martínez:** Methodology, Resources, Investigation. **Ana María Adalid-Martínez:** Methodology, Investigation. **Leandro Pereira-Dias:** Investigation, Writing - review & editing. **Cristina Casanova:** Investigation. **Elena Soler:** Investigation. **María Rosario Figàs:** Investigation. **María Dolores Raigón:** Methodology, Resources. **Mariola Plazas:** Methodology, Writing - review & editing, Supervision. **Salvador Soler:** Conceptualization, Resources, Supervision, Funding acquisition. **Jaime Prohens:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2021.110531.

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