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Nutritional and phytochemical characterization of radish (*Raphanus sativus*): A systematic review

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ABSTRACT

Background: Bioactive compounds in *Raphanus sativus* (radish) have been used to treat several diseases; therefore, radish has attracted increasing scientific attention due to its nutritional and phytochemical composition.
Scope and approach: The available evidence on the nutrient and bioactive composition of radish was systematically assessed. Four databases (PubMed, Embase, Web of Science, and Cochrane trials) were searched, up to September 26th, 2020, for key articles assessing the chemical composition of radish. Two independent reviewers carried out screening, selection of articles, and data extraction.
Key findings and conclusions: Of 1214 references, 63 met our inclusion criteria. We found 609 chemical compounds within 23 categories. Red (30% of all studied varieties), white (13%), and black (6%) radish were the most studied varieties. Nutrients and phytochemicals were reported mainly in roots and leaves. The largest categories were flavonoids (38.8% of the reported data), non-flavonoid polyphenols (8.4%), terpenes and derivatives (8.2%), fat and fatty related compounds (6.4%), and glucosinolates and breakdown products (5.6%). Leaves have high concentrations of macronutrients, calcium, potassium, sodium, fiber, fatty acids, and non-flavonoid polyphenols while sprouts are a major source of flavonoids, specifically anthocyanins, β-carotene and vitamin C. Roots are rich in non-flavonoid polyphenols together with terpenes and derivatives, and glucosinolates, the latter also highly concentrated in seeds. *Raphanus sativus* is a rich source of nutrients and phytochemicals. Leaves and sprouts could be considered part of a healthy diet, and together with roots, they could be explored as raw material for the development of nutraceuticals.

1. Introduction

One of the most commonly consumed vegetables is the *Brassicaceae* family, composed of leaves, roots, seasoning vegetables, and oilseeds (OECD, 2016), with approximately 310 genera and 3500 species (Al-Shehbaz, 2011, pp. 1–8). The importance of this vegetable family derives from its nutrient content, its contribution to the agricultural economy (Al-Shehbaz, 2011, pp. 1–8), and its chemical compounds with potential health benefits (Manivannan, Kim, Kim, Lee, & Lee, 2019).

Radish, known as *Raphanus sativus* L., is a species belonging to the genus *Raphanus* included in the Rapa/Oleacera lineage according to phylogenetic studies of the *Brassicaceae* family (Nishio, 2017). Radish is considered a root since its specialized structure (hypocotyls) has a full or partial subterranean habitat, its shape is close to the true roots, and it can store starch and other compounds (Radovich, 2018). The surface color of radish can vary from white in Asia to red in Europe through purple green and black (Nishio, 2017), while its flesh is white in most European and Asian crops (Hadley & Fordham, 2003). Certain

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characteristics of radish are due to its phytochemical content. Anthocyanin pigments provide the red color of roots, while a high potential to form isothiocyanates contributes to the pungent flavor and distinctive taste, which is highly popular in countries like Japan, the Philippines and Hawai (Gupta, Talwar, Jain, Dhawan, & Jain, 2003; Nishio, 2017). The edible part of radish is mainly the root. However, the consumption of leaves and sprouts is increasing (Butt, Sultan, & Lobo, 2018; Manivannan et al., 2019; Radovich, 2018; Xiao, Lester, Luo, & Wang, 2012). The root is usually consumed in salads, but it can also be cooked or salted together with other vegetables (Hadley & Fordham, 2003; Kaneko, Kimizuka-Takagi, Bang, & Matsuzawa, 2007; Nishio, 2017; Roy & Chakrabarti, 2003). Radish roots can also be processed as dried or canned pickles (Manivannan et al., 2019; Nishio, 2017), which are most commonly consumed in Asia (Roy & Chakrabarti, 2003). Leaves and sprouts are usually eaten raw as part of salads. Overall, radish is low in calories and a good source of calcium, magnesium, copper, manganese, potassium, vitamin B_6, vitamin C, and folate (Gupta et al., 2003; U.S. Department of Agriculture. Agricultural Research Service). According to data from the EPIC cohort in Europe, radish intake was 6% of the total of cruciferous or *Brassicaceae* vegetables, being fifth after cauliflower, broccoli, and white and normal cabbage (IARC, 2004).

Finally, radish extracts have been employed to treat several organ disorders (Hadley & Fordham, 2003; Manivannan et al., 2019). The potential use of radish as a source of bioactive compounds with clinical and health implications in diseases such as hypertension, cardiometabolic disorders and as an antimicrobial and antioxidant agent has become a field of interest for researchers and the pharmaceutical industry (T. K. Lim, 2012; Manivannan et al., 2019). Therefore, a comprehensive and systematic assessment of the nutrient and phytochemical composition of radish will allow a better understanding of its role in human nutrition and health, besides providing insights to prioritize future biological and pharmacological research about the wide range of phytochemicals contained in this vegetable. Compared to previous efforts, which are mainly narrative or expert reviews (Manivannan et al., 2019) and, consequently, may not capture the overall evidence on the topic, the present work systematically evaluated the nutrient and bioactive composition of *Raphanus sativus* (radish) and reported the concentration of its bioactive components for the first time.

2. Approach followed

2.1. Literature search

This review was conducted and reported following the PRISMA 10 statement (eAppendix 1) and based on the systematic review approach designed by Muka et al. (2019). Four bibliographic databases (PubMed, Embase, Web of Science, and Cochrane trials) were searched to identify published studies until September 26th, 2020 (date last searched) that examined the nutrient and bioactive composition of radish. The search terms were related to nutrient and bioactive compounds (e.g., nutrients, metabolism, phytochemical, carbohydrate, fatty acids) and the plant (radish) (eAppendix 2). No restrictions concerning language or date were applied. We excluded from the search conference abstracts, cost-effectiveness studies, letters to the editor, conference proceedings, literature reviews, systematic reviews or meta-analyses and, studies conducted with animals. To retrieve further relevant publications, we checked the reference lists of studies included in the current review (backward reference searching).

2.2. Study selection criteria

Studies were included if they met the following inclusion criteria: (i) used samples of any part of radish or seeds; and (ii) evaluated nutrient and bioactive compounds. We excluded studies in which radish was genetically manipulated and if the analysis included radish-based dietary supplements or meals. Two reviewers independently evaluated the titles and abstracts according to the selection criteria. For each potentially eligible study, two reviewers assessed the full-text. In cases of disagreement, a decision was made by consensus or, if necessary, a third reviewer was consulted.

2.3. Data extraction

Two reviewers extracted the data independently using a predesigned form, including first author, publication years, variety, cultivar (Cv.), analyzed part of the plant, compound name, concentrations, and biological activity reported in the articles. Other extracted information that could be of further interest has been collected in the supplemental Table 4 and includes the form in which the tissues were processed for analysis, the extracts/solvents, and the techniques used to identify/determine the phytochemicals.

2.4. Classification and report of compounds

All compounds were classified into categories according to their chemical structure. This cataloging was established using the PubChem Database of the US National Library of Medicine (S. Kim et al., 2018), which provides several types of chemical structure classifications. We used the "KEGG Phytochemical Compounds" classification, if available. Otherwise, we categorized the compounds using the "MeSH tree" classification. The compounds not identified or not included in the PubChem database were organized according to the category reported by the authors. Unclassified compounds were lumped into "other compounds". All categories and compounds are reported in alphabetical order or numerical order if the name starts with numbers or words denoting them.

The names of compounds were included as they were originally reported in papers, and to allow easy identification, we tagged them with their respective "PUBCHEM single Compound record" (CID) when possible. Compounds reported by more than one author with different names or terms were grouped under the same Pubchem CID. Authors reporting the same compound were listed according to publication year (from earliest to latest). Regarding the concentrations of the compounds, we reported the original units described in the papers. However, we converted the original units to mg/100 g of fresh weight (F.W.) or mg/100 g of dry weight (D.W.), when feasible, to facilitate comparability.

3. Major outcomes

The systematic search in the electronic databases (PubMed, Embase, Web of Science, and Cochrane trials) identified 1214 potentially relevant papers. After the abstract and full-text screening, we selected 45 articles and added 18 more by backward reference searching. Overall, we included a total of 63 papers for the final analysis (Fig. 1).

The information on the concentrations of biochemical compounds was reported in 41 of the 63 selected articles. The most studied varieties of radish were red (30% of all analyzed varieties), white (13%), and black (6%), included in 25, 11, and 5 articles, respectively (Supplemental Table 1). Twenty-six papers did not report the type of radish variety used. Regarding the plant's part analyzed in each study, roots were the most popular, with 26 articles studying them alone or together with other parts like leaves or sprouts (Supplemental Table 1 and Supplemental Table 2). After roots, leaves were the second most analyzed part being included in fourteen articles, nine of them comparing leaves with other parts, mainly roots. Findings on sprouts, seeds and stems were reported in eleven, seven, and three articles, respectively; four were based on the peel or skin of radish, and one last paper described results on cotyledons. Only one report analyzed all the radish parts, except for the leaves (Bhandari, Jo, & Lee, 2015). Thirteen of the 63 included articles did not clearly state which part of the radish was used. Among the 14 articles that reported analysis in at least two radish parts, leaves and roots were the most common combination being described in

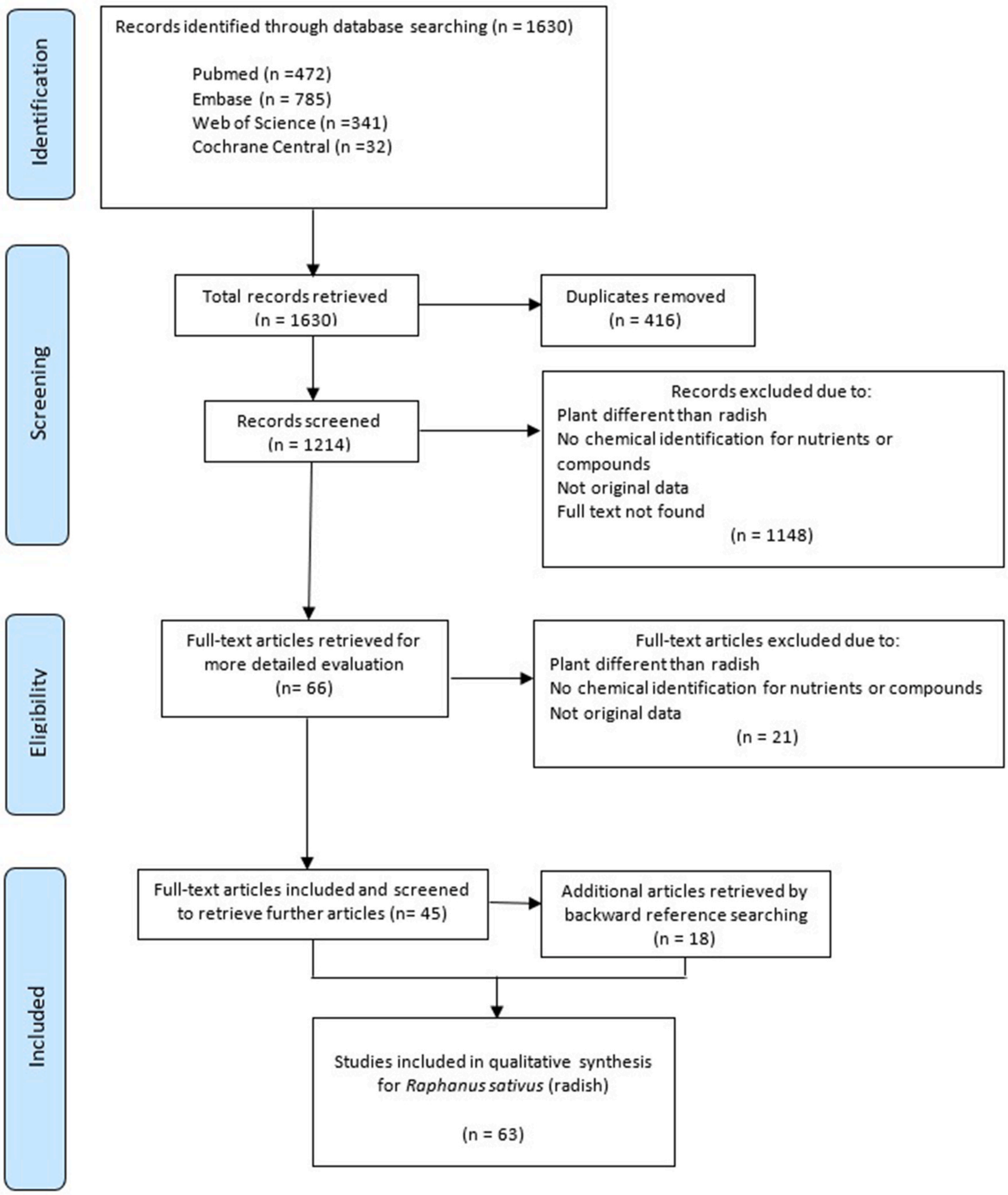

Fig. 1. Flowchart of studies reporting nutrients and bioactive composition of *Raphanus sativus*.

seven papers.

Overall, we found 609 chemical compounds reported in *Raphanus sativus*, allocated to 23 categories (supplemental Table 3). Flavonoids represent 38.8% of the reported bioactive compounds, followed by non-flavonoid polyphenols (8.4%), terpenes and derivatives (8.2%), fat and fatty related compounds (6.4%), glucosinolates and breakdown products (5.6%), and hydrocarbons (4.6%) (Fig. 2). Each of the remaining categories included less than 25 reported compounds (e.g. alkaloids (Agarwal & Varma, 2014; Gurav, Mondal, & Vijayakumar, 2014; Khamees, 2017; Sasaki et al., 2020), heterocyclics (Blažević & Mastelić, 2009; Chen et al., 2017; Revelou, Kokotou, & Constantinou-Kokotou, 2019, 2020) and enzymes included in the proteins category (Berger, Menudier, Julien, & Karamanos, 1996; Hata, Tanaka, Tsumuraya, & Hashimoto, 1992; Kikuchi, Saika, Yuasa, Nagahama, & Tsuji, 2008; Kotake et al., 2006; Lee Mi & Kim Soung, 1994)). Of the 609 reported compounds, information on concentrations was available only for 329 (54%) of them, grouped in 20 categories (supplemental Table 4). The only group without a quantitative report of its content was metabolites described by Onisko, Barnes, Staub, Walker, and Kerlinger (1994). Supplemental Table 2 also presents the compounds according to the parts of the plant in which they were reported. Twenty-two categories were studied in roots and leaves, seven were reported in sprouts, six in seeds, three in the skin, and nine in other radish parts (steam or cotyledons). For fourteen categories, the analyzed part of the plant was not reported.

Concerning the methods used to identify and quantify phytochemicals, we extracted information on the solvent or extract used to analyze every compound and the techniques to identify them (only for

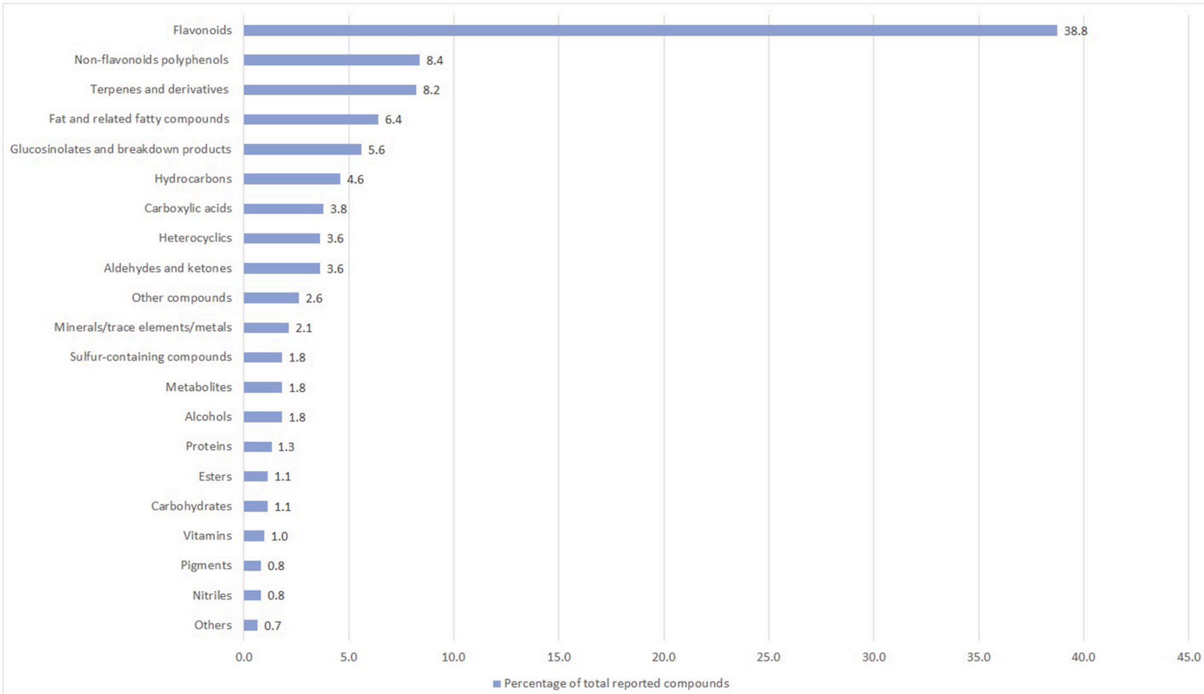

Fig. 2. Percentage of total reported compounds by categories of chemicals and bioactive compounds found in *Raphanus sativus*.
Chemical and bioactive compounds categorization is based on the phytochemical classifications proposed by Abbas et al. (2017), Durazzo et al. (2019) and Singla et al. (2019).

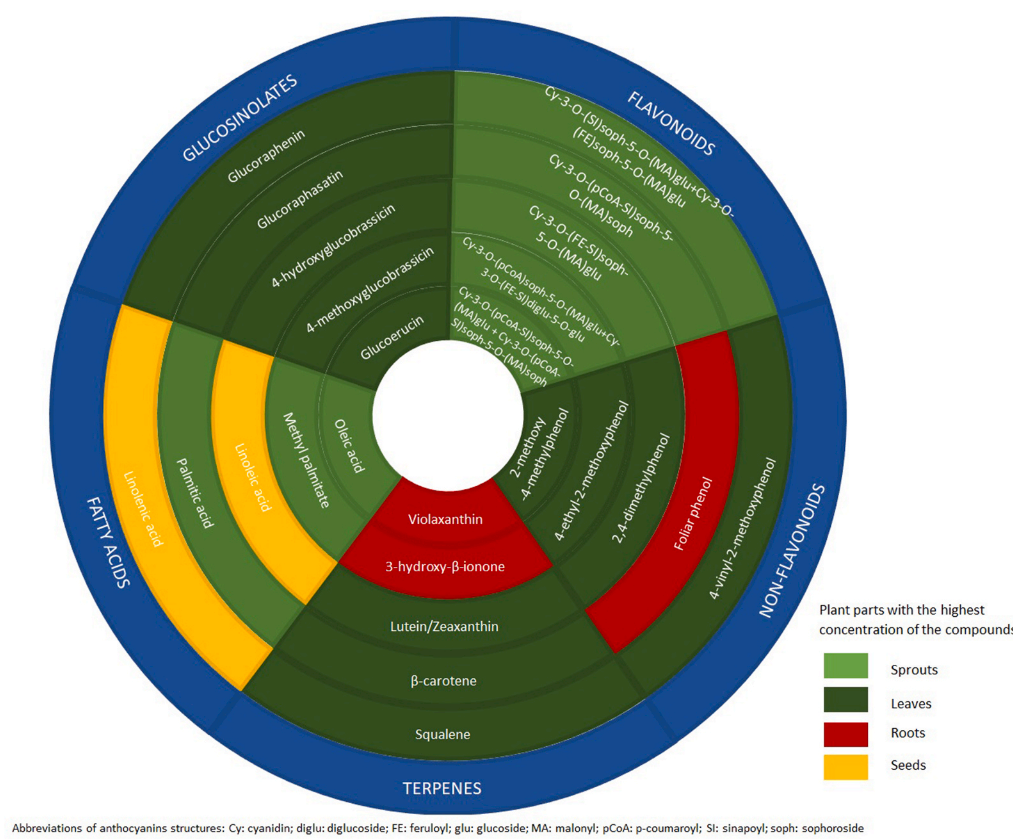

Fig. 3. Five most concentrated phytochemicals within the five major bioactive compounds categories in *Raphanus Sativus* (fresh weight).
External blue ring: chemical categories. From outside to inside of rings: the five most concentrated compounds by category in descending order.

compounds assessed quantitatively). As shown in supplemental Table 4, a wide variety of extracts/solvents and techniques are reported in the literature. The most reported form to prepare the radish tissues for analysis was lyophilization (50.3% of all compounds included in supplemental Table 4). The tissues' compounds were extracted mainly in methanol or mixtures of methanol and water extract. In those cases, the most common technique of analysis was high-performance liquid chromatography with diode-array detection (HPLC + DAD) or HPLC alone. For those compounds analyzed in fresh tissues (40.5%), hydrodistillation was the most common way to extract them. Techniques like gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-electrospray ionization-mass spectrometry (LC-ESI-MS) were the main methods applied to determine the bioactive molecules in fresh tissues.

Results were obtained for the proximate composition and the five main categories of bioactive compounds in *Raphanus sativus*: flavonoids; non-flavonoids polyphenols; terpenes and derivatives; fat, lipids, fatty acids and related fatty compounds; and glucosinolates and breakdown products. Fig. 3 shows the five most concentrated phytochemicals (mg/100 g F.W.) in these five main categories. We also briefly summarize the findings for other categories of nutrients and compounds because of their importance from a nutritional and health point of view.

3.1. Proximate composition of radish

Six papers reported qualitative and quantitative information on the proximate composition of radish (Ankita & Prasad, 2015; Ashraf, Sultana, Iqbal, & Mushtaq, 2016; Ashraf et al., 2018; Azam, Khan, Mahmood, & Hameed, 2013; Chihoub et al., 2019; Goyeneche et al., 2015). The total content of carbohydrates, fibers, lipids, proteins, and ash was reported in both roots and leaves. These three last categories were also analyzed in stems. A comparison of these chemicals' concentrations among all the articles was not possible since the reported units differed between them. However, we present in Table 1 the results obtained by Chihoub et al. (2019), Goyeneche et al. (2015), and Ankita and Prasad (2015), who compared the proximate composition of leaves, leaves together with stems, and roots in mg/100 g F.W. The data shows that leaves, compared to the root, are richer in macronutrients and fiber content. The concentration of proteins in leaves is almost seven times higher than the concentration described in roots (3810 mg/100 g F.W vs. 570 mg/100 g F.W, respectively), according to Goyeneche et al. (2015). However, Ankita and Prasad (2015) reported a lower value in leaves for this nutrient (123.7 mg/100 g F.W), even smaller than the one found by Goyeneche in roots (supplemental Table 4).

3.2. Flavonoids

This category accounted for more than a third of the included compounds in the systematic review. Thirty-three papers (Agarwal & Varma, 2014; Al Hilfi et al., 2019; Beevi, Narasu, & Gowda, 2010; Chihoub et al., 2019; Cunha et al., 2020; da Silva et al., 2020; Goyeneche et al., 2015; Gurav et al., 2014; Khamees, 2017; J. Y.; Kim et al., 2020; Papetti, Milanese, Zanchi, & Gazzani, 2014; Park et al., 2016; Shehata, Mahmoud, & Abdou, 2014; Yadav, Chatterji, Gupta, & Watal, 2014) identified 236 phytochemicals, of which 54 were quantitatively analyzed.

Anthocyanins were the most common subgroup of flavonoids, with 208 of them reported in 17 articles (Baenas, Ferreres, García-Viguera, & Moreno, 2015; Giusti, Ghanadan, & Wrolstad, 1998; Giusti, Rodriguez-Saona, et al., 1998; Hanlon & Barnes, 2011; Jiang & Zhou, 2019; Jing et al., 2012; Lin, Sun, Chen, & Harnly, 2011; Liu, Murakami, Wang, & Zhang, 2008; Matera et al., 2012; Otsuki, Matsufuji, Takeda, Toyoda, & Goda, 2002; Papetti et al., 2014; Park et al., 2016; Tamura, Tsuji, Yongzhen, Ohnishi-Kameyama, & Murakami, 2010; Tatsuzawa et al., 2010; Wang et al., 2010; Xianli Wu et al., 2006; X. Wu & Prior, 2005), although only 41 were analyzed for their concentrations in the plant (supplemental Tables 2 and 3). Anthocyanins were identified in roots, sprouts, and skin of several radish varieties. These compounds are present in nature in the forms of anthocyanidin glycosides and acylated anthocyanins. The most common types of anthocyanidins in fruits and vegetables are cyanidin (50% of the distribution), delphinidin (12%), pelargonidin (12%), peonidin (12%), petunidin (7%), and malvidin (7%) (Khoo, Azlan, Tang, & Lim, 2017). We found a similar composition for radish, with 59% of anthocyanidins identified as cyanidins, but in this case, pelargonidins are three times as expected (35%), and delphinidins account for only two percent of all reported anthocyanidins. Twelve pelargonidins and one cyanidin were the most identified in the literature, each of them being reported in at least three different papers (supplemental Table 3).

The five most concentrated anthocyanins among those described per mg/100 g F.W. are all forms of cyanidins identified in red radish sprouts (Table 1 and Fig. 3). When the results are standardized in mg/g D.W., pelargonidins in red radish show the highest concentrations (supplemental Table 4), although it is not possible to identify which part of the plant was analyzed. We found that the total anthocyanins content (TAC) ranges from 180 mg/100 g F.W. in red rambo radish sprouts (Baenas et al., 2015) to 11.6 mg/100 g F.W. in roots of red easter egg radish (Giusti, Rodriguez-Saona, et al., 1998). When comparing radish parts, specifically red radish, the TAC in mg/100 g F.W. was higher in sprouts with 180 mg/100 g F.W (Baenas et al., 2015) vs. 163 mg/100 g F.W. in the skin (Giusti, Rodriguez-Saona, et al., 1998) and 160.7 mg/100 g F.W. in roots (Jing et al., 2012). However, Hanlon and Barnes (2011) described their results in mg/g D.W. and found the opposite (Supplemental Table 4).

Besides anthocyanins, the most-reported flavonoid was the flavanol catechin, with two articles (Beevi et al., 2010; Papetti et al., 2014) identifying it in leaves, stem, and skin (supplemental Table 3). The highest concentrated non-anthocyanin flavonoids were flavonols. In mg/100 g D.W., it was myricetin with 641 mg/100 g D.W. in leaves of a non-specified radish variety (Table 1). In mg/g extract, the most concentrated one was kaempherol-3-O-rutinoside, with 7.2 mg/g extract in leaves and stems of an unknown radish variety (supplemental Table 4). There was no data described in mg/100 g F.W. for non-anthocyanin flavonoids. Regarding the total flavonoid content (TFC), it was measured in mg/100 g in fresh and dry weight, having the highest reported concentrations in red radish leaves (205 mg/100 g F.W) and in an unknown part (0.96 mg/100 g D.W.), respectively. Due to the diversity in measurement units used among studies to describe TFC, it was not possible to make further comparisons.

3.3. Non-flavonoids polyphenols and total polyphenol content (TPC)

Non-flavonoid polyphenols include phenolic acids, hydroxycinnamates, stilbenes, and tannins. With a total of 51 compounds identified in all parts of the plant in 24 articles (Agarwal & Varma, 2014; Al Hilfi et al., 2019; Ankita & Prasad, 2015; Ashraf et al., 2016; Ashraf et al., 2018; Beevi et al., 2010; Blažević & Mastelić, 2009; Chen et al., 2017; Chihoub et al., 2019; Cunha et al., 2020; da Silva et al., 2020; Goyeneche et al., 2015; Gurav et al., 2014; Hanlon & Barnes, 2011; Im et al., 2010; Jin, Ko, Chowdhury, Lee, & Woo, 2016; Khamees, 2017; J. K.; Kim, Baskar, & Park, 2016; Papetti et al., 2014; Park et al., 2016; Pushkala, Raghuram, & Srividya, 2013; Shehata et al., 2014; Takaya, Kondo, Furukawa, & Niwa, 2003; Tsouvaltzis & Brecht, 2014), this category is the second most reported chemical group in *Raphanus sativus*. Of the 51 reported non-flavonoid polyphenols, data on concentrations were available for 22 phytochemicals analyzed in 16 studies. The polyphenols identified in more than one paper are 4-ethyl-2-methoxyphenol, 4-vinyl-2-methoxyphenol, caffeic acid, p-coumaric acid, phenol, sinapic acid, and vanillic acid. These compounds, except caffeic acid, are also among the most concentrated phenols in *Raphanus sativus* (Table 1), with 4-vinyl-2-methoxyphenol (12.4 mg/100 g F.W., white radish) and vanillic acid (413 mg/100 g D.W., radish variety not reported) having the highest concentrations. It is noteworthy that the

Table 1
Proximate composition of *Raphanus sativus* and most concentrated compounds in the main five chemical categories according to the reported units of concentration.

No.	Compound name	PubChem CID	Variety	Cultivar	Concentration (mean)		Author (date of publication)
Proximate composition of radish (mg/100 g F.W.)					**Leaves**	**Roots**	
85	Ash	Not applicable	Not reported	Not reported	3185	Not analyzed	Chihoub et al. (2019)
	Ash	Not applicable	Red	Not reported	1700	770	Goyeneche et al. (2015)
91	Carbohydrates	Not applicable	White	NBH-White queen	5835	Not analyzed	Ankita and Prasad (2015)
	Carbohydrates	Not applicable	Red	Not reported	4040	3030	Goyeneche et al. (2015)
153	Crude fiber	Not applicable	White	NBH-White queen	2578	Not analyzed	Ankita and Prasad (2015)
	Crude fiber	Not applicable	Red	Not reported	610	320	Goyeneche et al. (2015)
217	Crude fat	Not applicable	White	NBH-White queen	412.5	Not analyzed	Ankita and Prasad (2015)
	Lipids	Not applicable	Red	Not reported	370	70	Goyeneche et al. (2015)
263	Crude protein	Not applicable	Red	Not reported	3810	570	Goyeneche et al. (2015)
Flavonoids					**Plant's part**	**Value**	
mg/100 g F.W.							
122	Cy-3-O-(SI)soph-5-O-(MA)glu + Cy-3-O-(FE)soph-5-O-(MA)glu	Not applicable	Red	Rambo	Sprouts	50.37	Baenas et al. (2015)
118	Cy-3-O-(pCoA-SI)soph-5-O-(MA)soph or Cy-3-O-(diFE)soph-5-O-(MA)soph	Not applicable	Red	Rambo	Sprouts	27.29	
110	Cy-3-O-(FE-SI)soph-5-O-(MA)glu	Not applicable	Red	Rambo	Sprouts	26.27	
119	Cy-3-O-(pCoA)soph-5-O-(MA)glu + Cy-3-O-(FE-SI)diglu-5-O-glu	Not applicable	Red	Rambo	Sprouts	23.5	
117	Cy-3-O-(pCoA-SI)soph-5-O-(MA)glu + Cy-3-O-(pCoA-SI)soph-5-O-(MA)soph or Cy-3-O- pCoA-SI)soph-5-O-(MA)soph + Cy-3-O-(FE-SI) soph-5-O-(MA)glu	Not applicable	Red	Rambo	Sprouts	15.19	
mg/g D.W.							
155	Myricetin	5281672	Not reported	Not reported	Leaves	6.41	Beevi et al. (2010)
145	Catechin	9064	Not reported	Not reported	Leaves	4.88	Beevi et al. (2010)
146	Epicatechin	72276	Red	Not reported	Leaves	3.22	Goyeneche et al. (2015)
156	Quercetin	5280343	Not reported	Not reported	Leaves	0.79	Beevi et al. (2010)
133	Pelargonidin 3-(feruloyl)diglucoside-5-(malonyl)glucoside	Not applicable	Red	Man tang hong	Not reported	0.47	Park et al. (2016)
Non-flavonoids polyphenols					**Leaves**	**Roots**	
mg/100 g F.W.							
248	4-vinyl-2-methoxyphenol (vinyl guaiacol)	332	White	Not reported	12.4	Traces	Blažević and Mastelić (2009)
254	Foliar phenol	996	Not reported	Not reported	2.7	3.7	Agarwal and Varma (2014)
244	2,4-dimethylphenol	7771	White	Not reported	3.2	Not analyzed	Blažević and Mastelić (2009)
247	4-ethyl-2-methoxyphenol	62465	Black	Not reported	2.6	Not analyzed	Blažević and Mastelić (2009)
243	2-methoxy-4-methylphenol	7144	White	Not reported	2.2	Not analyzed	Blažević and Mastelić (2009)
mg/100 g D.W.							
262	Vanillic acid	8468	Not reported	Not reported	413	Not analyzed	Beevi et al. (2010)
		8468	Red	Not reported	155.9	158.6	Goyeneche et al. (2015)
258	Sinapic acid	637775	Not reported	Not reported	321	Not analyzed	Beevi et al. (2010)
253	p-coumaric acid	637542	Red	Not reported	245.94	52.32	Goyeneche et al. (2015)
252	o-coumaric acid	637540	Not reported	Not reported	213	Not analyzed	Beevi et al. (2010)
261	Tyrosol	10393	Red	Not reported	180.47	Unquantifiable	Goyeneche et al. (2015)
Terpenes and derivatives			Leaves	Roots	Sprouts		

(*continued on next page*)

Table 1 (*continued*)

Terpenes and derivatives					Leaves	Roots	Sprouts	
mg/100 g F.W.								
322	Squalene	638072	Marushka	Not reported	Not analyzed	40.99	Not analyzed	Selyutina and Gapontseva (2016)
281	β-carotene	5280489	Not reported	Opal	Not analyzed	Not analyzed	6.3	Xiao et al. (2012)
			White	NBH-White queen	3.96	Not analyzed	Not analyzed	Ankita and Prasad (2015)
282	Lutein/Zeaxanthin	5281243/5280899	Not reported	Opal	Not analyzed	Not analyzed	5.5	Xiao et al. (2012)
297	3-hydroxy-β-ionone	5363700	White	Not reported	2.4	Not analyzed	Not analyzed	Blažević and Mastelić
283	Violaxanthin	448438	Not reported	Opal	Not analyzed	Not analyzed	2.3	Xiao et al. (2012)
mg/L					**Plant's part not reported**			
288	Carvone	7439	Red	Not reported	13.49			Chen et al. (2017)
291	(E)-geranyl acetone	1549778	Red	Not reported	11.65			
307	Camphene	6616	Red	Not reported	9.42			
296	Piperitone	6987	Red	Not reported	8.84			
308	Carvacrol	10364	Red	Not reported	6.83			
Fat, fatty acids and related fatty compounds					Leaves	Roots		
mg/100 g F.W.								
80	α-linolenic acid (C18:3n3)	5280934	Not reported	Not reported	73.3	Not analyzed		Chihoub et al. (2019)
	Linolenic acid	5280934	Marushka	Not reported	Not analyzed	4.389		Selyutina and Gapontseva (2016)
73	Palmitic acid (C16:0)	985	Not reported	Not reported	13.8	Not analyzed		Chihoub et al. (2019)
	Palmitic acid	985	Marushka	Not reported	Not analyzed	10.46		Selyutina and Gapontseva (2016)
79	Linoleic acid (C18:2n6)	5280450	Not reported	Not reported	12.9	Not analyzed		Chihoub et al. (2019)
	Linoleic acid	5280450	Marushka	Not reported	Not analyzed	8.69		Selyutina and Gapontseva (2016)
89	Methyl palmitate	8181	Daikon	Not reported	Not analyzed	9.07		Selyutina and Gapontseva (2016)
77	Oleic acid	445639	Marushka	Not reported	Not analyzed	7.62		Selyutina and Gapontseva (2016)
	Oleic acid (C18:1n9)	445639	Not reported	Not reported	3.13	Not analyzed		Chihoub et al. (2019)
mg/100 g D.W.								
73	C16:0, Palmitic acid	985	Not reported	Mino	Not analyzed	92		Azam et al. (2013)
80	C18:3n3, Linolenic acid	5280934	Not reported	Mino	Not analyzed	70		
79	C18:2c, Linoleic acid	5280450	Not reported	Mino	Not analyzed	32		
76	C18:0, Stearic acid	5281	Not reported	Mino	Not analyzed	19		
77	C18:1c, Oleic acid	445639	Not reported	Mino	Not analyzed	13		
Percentage F.W.								
73	Hexadecanoic acid (Palmitic acid)	985	Red	Not reported	8.5	49.9		Blažević and Mastelić
			Black	Not reported	14.3	32.2		
88	Methyl linolenate	5319706	Black	Not reported	11.1	21.7		
70	Tetradecanoic acid (Myristic acid)	11005	Black	Not reported	trace	1.9		
Glucosinolates and breakdown products: Semi-systematic chemical compound name (trivial compound name)					**Seeds**	**Sprouts**		
mg/100 g F.W								
167	(*R*)-4methylsulfinylbut-3-enylglucosinolate (glucoraphenin)	15559531	China rose	China rose	1052	32.8		Baenas et al. (2014)
166	4-methylthio-3-butenyl-glucosinolate (dehydroerucin or glucoraphasatin)	6442557	China rose	China rose	85.1	411		
158	4-hydroxy-3-indolylmethyl glucosinolate (4-hydroxyglucobrassicin)	656561	Red	Rambo	223	27.3		
159	4-methoxy-3-indolylmethyl glucosinolate (4-methoxyglucobrassicin)	656563	China rose	China rose	Not detected	27.2		
161	4-methylthiobutylglucosinolate (glucoerucin)	656539	China rose	China rose	Not detected	1.95		
μmol/g F.W.								
166	4-methylthio-3-butenyl-glucosinolate (glucoraphasatin)	6442557	Not reported	Not reported	Not analyzed	17.1		Yuan et al. (2010)
158	4-hydroxy-3-indolylmethyl glucosinolate (4-OH-glucobrassicin)	656561	Not reported	Not reported	Not analyzed	0.36		Yuan et al. (2010)
159	4-methoxy-3-indolylmethyl glucosinolate (4 Methoxybracissin)	656563	Not reported	Not reported	Not analyzed	0.15		Wei et al. (2011)
μmol/g D.W.					**Roots**	**Sprouts**		
166	4-methylthio-3-butenyl-glucosinolate (glucoraphasatin)	6442557	White	Miyashige	1.1	108.3		Hanlon and Barnes (2011)
167	(*R*)-4methylsulfinylbut-3-enylglucosinolate (glucoraphenin)	15559531	Red	Crunchy royale	2.1	53.8		Hanlon and Barnes (2011)

(*continued on next page*)

Table 1 (*continued*)

Fat, fatty acids and related fatty compounds					Leaves	Roots	
178	4-methylsulfinyl-3-butenyl isothiocyanate (sulforaphene)	11620	Not reported	Sango	Not analyzed	11.7	Matera et al. (2012)
Percentage F.W.					**Roots**	**Leaves**	
182	4-(methylthio)butyl isothiocyanate (erucin)	78160	White	Not reported	25.7	1.7	Blažević and Mastelić
183	5-(methylthio)-4-pentenenitrile	129730736	Black	Not reported	6.9	trace	
184	5-(methylthio)pentyl isothiocyanate (berteroin)	206037	White	Not reported	2	Not determined	

No.: Sequence number of the compounds according to their classification in supplemental Table 3.
F·W.: fresh weight, D.W.: dry weight.
Abbreviations of anthocyanins structures: Cy: cyanidin, diglu: diglucoside, FE: feruloyl, glu: glucoside, MA: malonyl, pCoA: p-coumaroyl, SI: sinapoyl, soph: sophoroside

highest concentrations of these compounds are found in leaves.

Regarding the TPC (supplemental Table 4), Shehata et al. (2014) obtained 29 mg/100 g F.W. in red radish leaves while Pushkala et al. (2013) found a smaller value in the roots (6.1 mg/100 g F.W.) of an unknown variety. Among the papers that reported the total content in mg of gallic acid equivalents (GAE)/100 g F.W. (Ashraf et al., 2018; Tsouvaltzis & Brecht, 2014), the highest concentration was found in the roots (14.6 mg GAE/100 g F.W.) of a non-described variety. Three articles (Goyeneche et al., 2015; Gurav et al., 2014; Hanlon & Barnes, 2011) described their results in mg GAE/100 g D.W.; in this case, the values for roots ranged from 422 mg GAE/100 g D.W (variety not described) to 0.2 mg GAE/100 g D.W (white radish). Goyeneche et al. (2015) got 695 mg GAE/100 g D.W in leaves (variety not specified). Lastly, Hanlon and Barnes (2011) analyzed several cultivars' sprouts, obtaining a mean of 1.97 mg GAE/100 g D.W.

3.4. Terpenes and derivatives

This group of phytochemicals consists of carotenoids, terpenes, terpenoids, triterpenoids and steroids. Fourteen papers (Agarwal & Varma, 2014; Ankita & Prasad, 2015; Ashraf et al., 2016; Ashraf et al., 2018; Blažević & Mastelić, 2009; Chen et al., 2017; Cunha et al., 2020; Khamees, 2017; Kovacs, Silaghi-Dumitrescu, Kovacs, & Roman, 2020; Ragasa, Ebajo, Tan, & Shen, 2015; Selyutina & Gapontseva, 2016; Takaya et al., 2003; Xiao et al., 2012; Yadav et al., 2014) described 50 compounds, of which 42 were analyzed quantitatively. This category was mainly studied in roots and leaves, a few papers presented their results in sprouts and seeds (Khamees, 2017; Takaya et al., 2003; Xiao et al., 2012), and only two articles (Chen et al., 2017; Kovacs et al., 2020) did not specify the studied plant's part.

The most identified compounds were β-carotene and phytol with four and three citations, respectively (supplemental Table 3). Concerning the quantitative analysis, when the values are described as mg/100 g F.W. (Table 1), squalene in marushka radish roots appears in the first place (40.9 mg/100 g F.W.), followed by two carotenoids in the second and third positions (β-carotene and lutein/zeaxanthin in the sprouts of opal cultivar with 6.3 mg/100 g F.W. and 5.5 mg/100 g F.W., respectively). By comparing the concentrations of β-carotene according to the studied plant's part (supplemental Table 4), we found that sprouts contain almost three times the amount present in leaves (mean concentrations: 5.9 mg/100 g F.W. and 2.2 mg/100 g F.W, respectively). As for other concentration measurement units in this category, Chen et al. (2017) used mg/L to describe their findings in red radish, reporting carvone as the most concentrated phytochemical (13.49 mg/L). None of the most concentrated terpenes and derivatives reported in mg/L coincides with the most concentrated ones in mg/100 g F.W.

3.5. Fat, lipids, fatty acids, and related fatty compounds

Thirty-nine chemicals identified in 12 papers (Ankita & Prasad, 2015; Azam et al., 2013; Blažević & Mastelić, 2009; Chang, Shi, Hu, & Shuai, 2019; Chen et al., 2017; Chihoub et al., 2019; Goyeneche et al., 2015; Liberati-Čizmek et al., 2019; Ragasa et al., 2015; Selyutina & Gapontseva, 2016; Takaya et al., 2003; Vidrih, Filip, & Hribar, 2009) compose this category. The phytochemicals most frequently analyzed were α-linolenic acid with seven papers, palmitic and linoleic acids with five articles each of them, and myristic, pentadecanoic, and oleic acids included in four reports (supplemental Table 3). Except for the pentadecanoic and myristic acids, the most frequently analyzed compounds are also the most concentrated in radish (Table 1). For the 37 chemicals quantified in this group, there was heterogeneity between papers regarding the units used to report concentrations (mg/100 g F.W., mg/D.W., and percentage of F.W.). Linolenic acid is the most concentrated compound in mg/100 g F.W. (73.3 mg/100 g F.W.), while palmitic acid ranks first in mg/100 g D.W. and percentage of F.W. (92 mg/100 g D.W. and 49.9% F.W.). Among those articles that compared leaves and roots, the highest values were almost always reported in leaves when expressed as mg/100 g F.W. The opposite was observed when the concentrations were described in percentages of F.W.

3.6. Glucosinolates and breakdown products

Radishes are unique among the cruciferous plants because of their glucosinolates, which are the precursor compounds to isothiocyanates. Glucosinolates are anions composed of thiohydroximates carrying an S-linked β-glucopyranosyl residue and an O-linked sulfate residue, and with an amino acid derived, variable side chain; occasionally, further substituents are attached to O, S or N atoms of the side chain or glucosyl moiety (Agerbirk & Olsen, 2012). Glucosinolates are thought to be stored in the vacuole of plant's cells (Andréasson & Jørgensen, 2003). Upon physical damage to the plant, glucosinolates interact with myrosinase, an enzyme that catalyzes the rapid breakdown to intermediate products that become isothiocyanates, thiocyanates, nitriles, or epithionitriles (Wittstock, Kurzbach, Herfurth, & Stauber, 2016). The pH and presence of specifier proteins (NSP, nitrile-specifier protein, ESP, epithiospecifier protein, TFP, thiocyanate-forming protein) guide the formation of one of these end product types (Kuchernig, Burow, & Wittstock, 2012; O'Hare et al., 2007). Fifteen papers (Agarwal & Varma, 2014; Ankita & Prasad, 2015; Baenas, García-Viguera, & Moreno, 2014; Bhandari et al., 2015; Blažević & Mastelić, 2009; Chang et al., 2019; Chen et al., 2017; Hanlon & Barnes, 2011; Im et al., 2010; Jing et al., 2012; Matera et al., 2012; Selyutina & Gapontseva, 2016; Sun & Chen, 2019; Wei, Miao, & Wang, 2011; Yuan, Wang, Guo, & Wang, 2010) reported qualitatively and quantitatively 34 glucosinolates and breakdown products in all the radish parts.

With specific reference to glucosinolates, 4-methylthiobut-3-enylglucosinolate (glucoraphasatin) was the most frequently reported compound among articles analyzing this category (supplemental Table 3). It was also the compound with the highest concentration (Table 1) when results were reported in μmol/g F.W. (17.1 μmol/g F.W., unknown radish variety) and μmol/g D.W. (108.3 μmol/g D.W., white variety). Interestingly, both mentioned values were described in radish sprouts.

Finally, Baenas et al. (2014) compared seeds and sprouts of two radish varieties in mg/100 g F.W., finding that (*R*)-4methylsulfinylbut-3-enylglucosinolate (glucoraphenin) was the most concentrated glucosinolate, and its concentration was six-fold in seeds than in sprouts (1052 mg/100 g F.W. in China rose radish vs. 167 mg/100 g F.W. in red radish, respectively); in this case, glucoraphasatin ranked second with 411 mg/100 g F.W. in sprouts of china rose radish. About total glucosinolate content (TGC), Baenas et al. (2014) reported 1293 mg/100 g F.W. in seeds of china rose radish while Jing et al. (2012) analyzed it in mg/100 g D.W. in red radish roots (Xin Ling Mei Cv.), finding 163.1 mg/100 g D.W. as the largest amount. The highest TGC in μmol/g F.W. was described by Yuan et al. (2010) in sprouts of an unknown variety (17.55 μmol/g F.W.) while in μmol/g D.W., Hanlon and Barnes (2011) reported 133.9 μmol/g D.W. in white miyashige radish sprouts; this amount is remarkable when compared with 21 μmol/g D.W. in the same cultivar roots.

Concerning the breakdown products of glucosinolates, we found isothiocyanates and thiocyanates. These phytochemicals were analyzed in radish roots, leaves, and sprouts (supplemental Table 3). Four different papers reported 4-(methylthio)-3-butenyl isothiocyanate (raphasatin), making it the most frequently reported intermediate product. As for the analysis of concentrations (Table 1), when the data was described in percentage, 4-(methylthio)butyl isothiocyanate (erucin) presented the highest concentration with 25.7% in white radish roots. In mg/100 g D.W., the only analyzed compound was 4-(methylsulfinyl)butyl isothiocyanate (sulforaphane) (Im et al., 2010); its highest concentration in roots was quantified in white radish (5.26 mg/100 g D.W.), but it was also identified in leaves where the highest concentration was reported in red radish (4.21 mg/100 g D.W.) (supplemental Table 4). With reference to the total isothiocyanates content (TIC), we specifically refer to those articles that allowed a comparison of results regarding the measurement unit. Matera et al. (2012), Hanlon and Barnes (2011), and Sun and Chen (2019) described their findings in μmol/g D.W. The highest concentration of TIC was reported by Matera et al., who found 77.8 μmol/g D.W. in sprouts of sango cultivar (variety unknown), while Hanlon and Barnes reported 77.6 μmol/g D.W. in sprouts of red radish as the highest concentration. These concentrations are far from the results obtained by Sun and Chen in red radish (1.43 μmol/g D.W.).

3.7. Other compounds categories

Considering the nutritional and health importance of other compounds categories that were not among the largest five, we describe the results for the categories minerals/trace elements/metals and vitamins.

There were 13 minerals and trace elements studied and quantified in several radish parts by three reports (Azam et al., 2013; Goyeneche et al., 2015; Guevara Moreno, Acevedo Aguilar, & Yanez Barrientos, 2018). The analyzed amounts of calcium, iron and zinc in mg/100 g F.W. of red radish were, in all cases, higher in leaves than those reported in roots (supplemental Table 4). Calcium is the most concentrated mineral (752.6 mg/100 g F.W. in leaves vs. 147.8 mg/100 g F.W. in roots). The iron value in leaves is three times higher than in roots. The zinc content is quite similar in both parts of the radish. When the results are reviewed in mg/g D.W., Guevara Moreno et al. (2018) reported in a non-described part of an unknown variety of radish 501 mg/g D.W. of molybdenum ranking it as the most concentrated and followed by selenium with 203 mg/g D.W. and zinc with 95.1 mg/g D.W.

In the vitamins category, eight articles (Agarwal & Varma, 2014; Ankita & Prasad, 2015; Azam et al., 2013; Chihoub et al., 2019; Goyeneche et al., 2015; Pushkala et al., 2013; Tsouvaltzis & Brecht, 2014; Xiao et al., 2012) described their findings for phylloquinone, α-tocopherol, γ-tocopherol, L-ascorbic acid (known as vitamin C) and its oxidation product, dehydroascorbic acid in sprouts, leaves, stems and roots (supplemental Table 3). Vitamin C is not only the most studied, being reported in six papers, but it is also the most concentrated one with 95.8 mg/100 g F.W. in sprouts of china rose Cv. (supplemental Table 4). This value is up to 2.5 times higher when compared with the highest value in leaves (38.6 mg/100 g F.W.). Ranked as the second most concentrated vitamin appears α-tocopherol, which was analyzed in sprouts of three different cultivars by Xiao et al. (2012) with a maximum value of 87.4 mg/100 g F.W. in green daikon Cv. and a minimum of 0.0197 mg/100 g F.W. in china rose Cv. Chihoub et al. (2019) also reported α-tocopherol in mg/100 g F.W. with a value of 0.32 mg/100 g F.W. in leaves and stems of a non-specified variety.

3.8. Compounds with highest concentrations in Raphanus sativus

In Table 2, we have summarized the 20 most concentrated compounds reported in mg/100 g F.W. Macronutrients, fiber, glucosinolates, carboxylic acids, and some minerals (calcium and potassium) are ranked in the first ten positions. Remarkably, most of them are more concentrated in leaves (except glucosinolates, which are more concentrated in seeds) than in roots. The total content of phytochemicals like carboxylic acids, flavonoids and anthocyanins are also among the most concentrated values, with sprouts being the richest part of radish in anthocyanins but also in vitamin C. Some other compounds appearing in the top 20 most concentrated are sodium, 4-hydroxy-3-indolylmethyl glucosinolate (4-OH-glucobrassicin), total sugars, chlorophyll total, and fructose.

4. Discussion

From the results of 63 papers on the nutritional and phytochemical composition of *Raphanus sativus*, our review identified 609 phytochemicals in radish, with major constituents like flavonoids, non-flavonoid polyphenols, fat and fatty related compounds, terpenes and derivatives, and glucosinolates being reported in high concentrations in leaves and sprouts. These results highlight the contribution of this plant to a healthy and balanced diet. We found that leaves and sprouts have a higher nutritional value and a higher content of bioactive compounds compared to the roots; these conclusions are also shared by other authors like Chihoub et al. (2019) and Baenas, Gómez-Jodar, Moreno, García-Viguera, and Periago (2017). However, this composition depends on the radish variety and cultivar. Most of our findings are based on red, black, and white radish, and further research is needed to identify and quantify the nutrients and bioactive components in other varieties and cultivars.

When possible, we compared our findings to the nutritional information presented by the U.S. Department of Agriculture (USDA) (U.S. Department of Agriculture. Agricultural Research Service) for raw radish. For proximate composition, the USDA reports 3400 mg/100 g F.W. of carbohydrates, 100 mg/100 g F.W. of fat, and 680 mg/100 g F.W. of protein, all similar values to those reported by Goyeneche et al. (2015) for roots. We found for all the above compounds that their concentrations are higher in leaves. In the case of fiber, the amount described by the USDA is five times higher (1600 mg/100 g F.W.) than the one reported for roots, but still lower when compared with 2578 mg/100 g F.W. reported by Ankita and Prasad (2015) in white radish leaves. Concerning fatty acids, we compared the top five most concentrated fatty acids reported in mg/100 g F.W. in leaves and stems (Chihoub et al., 2019), and roots (Selyutina & Gapontseva, 2016) with the amounts in mg/100 g F.W. described by the USDA database. We found that most articles have lower levels than those provided by the USDA (palmitic acid 13.8 mg/100 g F.W. vs. 27 mg/100 g F.W.; linoleic acid 12.9 mg/100 g F.W. vs. 31 mg/100 g F.W.; oleic acid 7.6 mg/100 g F.W. vs. 17 mg/100 g F.W.), except for the linolenic acid, which according to Chihoub et al. (2019), is 2.3 fold higher than the USDA value (73.3 mg/100 g F.W. in leaves and stems vs. 31 mg/100 g F.W.). Another comparison shows that β-carotene values (Xiao et al., 2012) (mean 5.9 mg/100 g F.W.) exceed by far those reported by the USDA for radish sprouts (0.24 mg/100 g F.W.) or raw radish (0.004 mg/100 g F.W.).

Table 2
Most concentrated compounds (mg/100 g F.W.) in *Raphanus sativus*.

Rank	No.	Category	Compound name	PubChem CID	Variety	Cultivar	Concentration mg/100 g F.W. (mean)				Author (date of publication)
							Leaves	Roots	Sprouts	Seeds	
1	40	Carbohydrates	Carbohydrate	NAp	White	NBH-White queen	5835	NA	NA	NA	Ankita and Prasad (2015)
					Red	NR	4040	3030	NA	NA	Goyeneche et al. (2015)
2	269	Proteins	Crude protein	NAp	Red	NR	3810	570	NA	NA	Goyeneche et al. (2015)
3	103	Fiber	Crude fiber	NAp	White	NBH-White queen	2578	NA	NA	NA	Ankita and Prasad (2015)
					Red	NR	610	320	NA	NA	Goyeneche et al. (2015)
4	171	Glucosinolates	Total glucosinolates	NAp	China rose	China rose	NA	NA	488	1293	Baenas et al. (2014)
5	61	Carboxylic acids	Organic acids sum	NAp	NR	NR	1138	NA	NA	NA	Chihoub et al. (2019)
6	167	Glucosinolates	(*R*)-4methylsulfinylbut-3-enylglucosinolate (glucoraphanin)	15559531	China rose	China rose	NA	NA	32.8	1052	Baenas et al. (2014)
7	45	Carboxylic acids	Citric acid	311	NR	NR	755.5	NA	NA	NA	Chihoub et al. (2019)
8	224	Minerals	Calcium	5460341	Red	NR	752.6	147.8	NA	NA	Goyeneche et al. (2015)
9	228	Minerals	Potasium	5462222	Red	NR	495.3	380.1	NA	NA	Goyeneche et al. (2015)
10	102	Fat and related compounds	Crude fat	NAp	White	NBH-White queen	412.5	NA	NA	NA	Ankita and Prasad (2015)
			Lipids	NAp	Red	NR	370	70	NA	NA	Goyeneche et al. (2015)
11	166	Glucosinolates	4-methylthio-3-butenyl-glucosinolate (glucoraphasatin)	6442557	China rose	China rose	NA	NA	85.1	411	Baenas et al. (2014)
12	58	Carboxylic acids	Oxalic acid	971	NR	NR	388.7	NA	NA	NA	Chihoub et al. (2019)
13	232	Minerals	Sodium	5360545	Red	NR	298.5	104.9	NA	NA	Goyeneche et al. (2015)
14	158	Glucosinolates	4-hydroxy-3-indolylmethyl glucosinolate (4-OH-glucobrassicin)	656561	Red	Rambo	NA	NA	27.3	223	Baenas et al. (2014)
15	157	Flavonoids	Total flavonoid	NAp	Red	NR	204.9	NA	NA	NA	Shehata et al. (2014)
16	144	Flavonoids	Total anthocyanins	NAp	Red	Rambo	NA	NA	180	NA	Baenas et al. (2015)
					Red	Yan Zhi# 2	NA	160.7	NA	NA	Jing et al. (2012)
17	39	Carbohydrates	Total sugars	NA	NR	NR	156.4	NA	NA	NA	Chihoub et al. (2019)
18	268	Pigments	Chlorophyll total	6449992	White	NBH-White queen	105.7	NA	NA	NA	Ankita and Prasad (2015)
19	323	Vitamins	Total ascorbic acid	54670067	NR	China rose	NA	NA	95.8	NA	Xiao et al. (2012)
			Vitamin C	54670067	NR	Mino	NA	38.8	NA	NA	Azam et al. (2013)
			Ascorbic acid		Red	NR	38.6	16.5	NA	NA	Goyeneche et al. (2015)
20	35	Carbohydrates	Fructose	2723872	NR	NR	90.8	NA	NA	NA	Chihoub et al. (2019)

No.: Sequence number of the compounds according to their classification in supplemental table 4.
N.I.: Not included in PUBCHEM.
NR: Not reported.
NA: Not analyzed.
Nap: Not applicable.

Thus, one portion (one cup or 40 g according to the USDA) of radish sprouts (cultivars opal or green daikon or china rose) provides a mean of 197 µg RAE (retinol activity equivalents), which is a quarter of the recommended dietary allowance (RDA) for vitamin A in adults (900 µg RAE/day for men and 700 µg RAE/day for women) (Institute of Medicine, 2001). This makes sprouts of the cultivars mentioned above an excellent source of vitamin A. When comparing the mineral content for red roots found by Goyeneche et al. (2015) with that informed by the USDA, the only remarkable differences lie in calcium and sodium, which are 6 and 2.5 times higher in the mentioned article, respectively. Therefore, one portion of red radish roots (1 cup chopped, 55 g) covers 41% of the RDA for this mineral (1000 mg/day, adults 19–50 years old) (Institute of Medicine, 2011), and can be considered as a source of calcium. Lastly, for vitamin C reported in F.W., both in sprouts (Xiao et al., 2012) and roots, our findings revealed higher levels compared to USDA levels (95.8 mg/100 g F.W. vs. 28.9 mg/100 g F.W. and 38.8 mg/100 g F.W. vs. 14.9 mg/100 g F.W., respectively). Overall, we highlight the disparity in the published USDA levels compared to those found in the literature. It would be beneficial that public databases for nutritional and bioactive compounds regularly update their information, considering the ongoing evidence in this field.

To better understand the radish role as part of the *Brassicaceae* family, we have compared our findings (mg/100 g F.W.) regarding the leaves and roots proximal composition and the content of certain minerals and vitamins with other raw vegetables like cabbage, cauliflower, broccoli, arugula, and turnip in Table 3. Remarkably, the protein content of the radish leaves (3810 mg/100 g F.W.) is the highest, followed by broccoli and arugula (2820 mg/100 g F.W. and 2580 mg/100 g F.W., respectively). Radish leaves fat and carbohydrates content is intermediate, while the amount of these two macronutrients in the root is the lowest. These characteristics make radish an adequate food to be considered in diets attempting weight reduction. The fiber content is the lowest among all vegetables included for comparison (320 mg/100 g F.W. in the root and 610 mg/100 g F.W. in the leaves), making radish a suitable food for low-residue diets while still offering a fair amount of protein. The amounts of potassium and calcium present in the radish leaves (495 mg/100 g F.W. and 752 mg/100 g F.W., respectively) are the highest among the compared Brassicaceae vegetables, suggesting radish can be part of a healthy diet in individuals with cardiometabolic disorders or for those with high mineral requirements such as athletes. Concerning vitamins, the radish level of vitamin C ranks third after broccoli and cauliflower and has a similar amount as cabbage. As for β-carotene, the radish leaves possess the highest concentration, containing up to threefold the amount present in the other compared vegetables allowing radish leaves to be considered a source of vitamin A among the Brassicaceae family.

For other phytochemicals content, certain articles allowed a comparison of radish with more than one *Brassicaceae* vegetable. Bhandari et al. (2015) compared the TGC in μmol/g D.W. of all the radish parts with those of broccoli, cabbage, and cauliflower, finding in all cases that radish parts presented the lowest values among the mentioned vegetables. When Sun and Chen (2019) compared radish TGC values in nmol/g D.W. against arugula, broccoli, cauliflower, and turnip, black radish ranked third after broccoli and arugula (1279 nmol/g D.W, 1,925 nmol/g D.W and 1600 nmol/g D.W, respectively). Lastly, Shehata et al. (2014) analyzed the TFC content in mg/100 g F.W. in leaves of radish, cabbage, and cauliflower, among other vegetables. Red and white radish leaves were second after cauliflower (204 mg/100 g F.W., 138 mg/100 g F.W., and 299 mg/100 g F.W., respectively). The different varieties and cultivars of the compared vegetables make it challenging to assess their phytochemical contribution among the *Brassicaceae* family. However, radish has proved to be an important source of the several studied nutrients and bioactive compounds reported in this review.

The phytochemicals identified in this review establish linkages to the underlying mechanisms on the health benefits of radish. Some of the radish compounds are known to have several health benefits, including antioxidant/redox activity, anticancer and apoptosis-inducing properties, cardiovascular and metabolic protective effect, and antimicrobial and anti-inflammatory characteristics, among others (Manivannan et al., 2019). The antioxidant activity of radish lies mainly in its leaves and sprouts since they possess a higher radical scavenging ability confirmed in in-vitro and in-vivo research (Agarwal & Varma, 2014; Beevi et al., 2010; Bischoff, 2016; Lugasi, Blázovics, Hagymási, Kocsis, & Kéry, 2005) and mediated by their higher content on glucosinolates, anthocyanins, ascorbic acid, and polyphenols. Hence, radish leaves and sprouts may play a significant role in preventing oxidative stress-related diseases (Agarwal & Varma, 2014). Regarding the chemopreventive and apoptosis-inducing properties of radish, it is known that isothiocyanates act as modulators of enzymatic detoxification, apoptotic induction, oxidative stress generation, signal transduction, epigenetic induction, selective antiproliferative activity and anti-angiogenesis and anti-inflammatory activity, among other mechanisms related to cancer prevention (Atwell et al., 2015; Hać et al., 2019; Mitsiogianni et al., 2019; Vig, Rampal, Thind, & Arora, 2009). The protecting effect of radish on cardiometabolic disorders has also been studied. In diabetes, studies have shown improvement of glycemic profile by reducing intestinal glucose absorption, reducing glucose-induced oxidative stress, and improving insulin sensitivity (Banihani, 2017). For cardiovascular protection, the nitrite content in radish may improve the vascular homeostasis through the increase of nitric oxide; processes like atherosclerosis might be slowed due to the anti-inflammatory properties of isothiocyanates (Blekkenhorst et al., 2018; Kuroda, Kazumura, Ushikata, Minami, & Kajiya, 2018), even after vascular damage sulforaphane, one of the isothiocyanates in radish can prevent restenosis (Kwon et al., 2012). Radish may also facilitate antimicrobial activity associated with an inhibitory effect on gram-positive and negative bacteria's growth and acting as an antifungal. These properties have been associated with the presence of phenols like caffeic acid and ferulic acid (Salah-Abbès, Abbès, Haous, & Oueslati, 2009). Sulforaphene, an isothiocyanate found in radish, has shown strong antibacterial activity in gram-positive bacteria, especially against drug-resistant strains of *H. pylori* and methicillin-resistant *Staphylococcus aureus* (S. Lim, Han, & Kim, 2016). Flavonoids, saponins, and tannins present in radish have also demonstrated antimicrobial activity (Ahmad, Hasan, Chishti, & Ahmad, 2013).

Finally, it is worth considering radish's organoleptic characteristics since its particular flavor can influence its acceptability among the consumers. In radish, the main compound associated with its characteristic "pungent" flavor is 4-(methylthio)-3-butenyl isothiocyanate, also known as raphasatin (Bell, Oloyede, Lignou, Wagstaff, & Methven, 2018), which we have found to be the most reported isothiocyanate produced from the breakdown of 4-methylthiobut-3-enylglucosinolate (glucoraphasatin). Glucoraphasatin ranked as one of the most concentrated glucosinolates in radish, particularly in its sprouts but also present

Table 3
Nutritional composition of *Raphanus sativus* and other commonly consumed vegetables of the *Brassicaceae* family (mg/100 g F.W.).

Phytochemical/Nutrient	Radish* (root)	Radish* (leaves)	Cabbage green[a]	Cauliflower[a]	Broccoli[a]	Arugula[a]	Turnip[a]
Proteins	570	3810	1280	1920	2820	2580	900
Fat	70	370	100	280	370	660	100
Carbohydrates	3030	4040	5800	4970	6640	3650	6430
Fiber	320	610	2500	2000	2600	1600	1800
Potasium	380	495	170	299	316	369	191
Calcium	148	752	40	22	47	160	30
Vitamin C	38.8**	38.6	36.6	48.2	89.2	15	21
β-carotene	NA	3.96***	0.005	0	0.3	1.4	0

F.W.: Fresh weight.
NA: Not analyzed.
*Highest value reported for radish roots and leaves by Goyeneche et al. (2015).
**Highest value reported for radish roots by Azam et al. (2013).
***Highest value reported for radish leaves by Ankita and Prasad (2015).
[a] U.S. Department of Agriculture, Agricultural Research Service. FoodData Central USDA (U.S. Department of Agriculture. Agricultural Research Service, 2020).

in other parts like roots and seeds (Table 1). Pungency differs among radish cultivars, environmental growth factors, agronomic and cooking practices, but its acceptance among diverse populations has been linked with genetic traits related to taste and olfactory receptors and, therefore, gastronomical appreciation of this vegetable varies widely (Bell et al., 2018). More research could be performed in the future to better understand the palatability of radish according to its pungency and how this impacts its inclusion in a healthy diet.

5. Conclusions

Raphanus sativus (radish) is a source of nutrients and phytochemicals, particularly proteins, glucosinolates, flavonoids, β-carotene, and minerals. Many of these phytochemicals are highly concentrated in leaves and sprouts, which could be considered part of a healthy diet, especially in western diets where the root consumption is prioritized. Both sprouts and leaves can also improve the organoleptic characteristics of the dishes where they are used as ingredients. Radish can also be considered raw material for the development of nutraceuticals targeting both infectious and non-communicable diseases. Further studies are needed to determine which varieties and cultivars of radish yield the best nutrition and phytochemical profile. We also encourage researchers to continue investigating the nutritional and phytochemical composition of the aerial parts of radish and its sprouts as there are still knowledge gaps in categories like vitamins and minerals, and these parts of the plant have demonstrated potential to combat micronutrient deficiencies as in the β-carotene case.

Author's contribution

Oscar H. Franco, Hua Kern and Taulant Muka: conceptualization. Taulant Muka: methodology and supervision. Beatrice Minder: search strategy creation and online database search. Magda Gamba, Eralda Asllanaj, Peter Francis Raguindin, Marija Glisic and Taulant Muka: investigation and formal analysis. Magda Gamba, Hua Kern and Taulant Muka: Writing - Original Draft. Eralda Asllanaj, Peter Francis Raguindin, Marija Glisic, Oscar H. Franco, Beatrice Minder, Weston Bussler, Brandon Metzger: Writing - Review & Editing. All authors approved the final version of the manuscript.

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Appendix A. Supplementary data

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