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Original Research Article

Characterization of Phenotypic Traits and Evaluation of Glucosinolate Contents in Radish Germplasms (*Raphanus sativus* L.)

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Abstract - The edible roots of radish (*Raphanus sativus* L.) are consumed worldwide. For characterization and evaluation of the agronomic traits and health-promoting chemicals in radish germplasms, new germplasm breeding materials need to be identified. The objectives of this study were to evaluate the phenotypic traits and glucosinolate contents of radish roots from 110 germplasms, by analyzing correlations between 10 quantitative phenotypic traits and the individual and total contents of five glucosinolates. Phenotypic characterization was performed based on descriptors from the UPOV and IBPGR, and glucosinolate contents were analyzed using liquid chromatography-tandem mass spectrometry in multiple reaction monitoring mode (MRM). Regarding the phenotypic traits, a significant correlation between leaf length and root weight was observed. Glucoraphasatin was the main glucosinolate, accounting for an average of 71% of the total glucosinolates in the germplasms; moreover, its content was significantly correlated with that of glucoerucin, its precursor. Principal component analysis indicated that the 110 germplasms could be divided into five groups based on their glucosinolate contents. High levels of free-radical scavenging activity (DPPH) were observed in red radishes. These results shed light on the beneficial traits that could be targeted by breeders, and could also promote diet diversification by demonstrating the health benefits of various germplasms.

Key words - Chatracterization, Evaluation, Germplasm, Glucosinolate, Radish

Introduction

The edible roots of radish (*Raphanus sativus* L., 2n = 2x = 18), a representative of the *Raphanus* genus in the Brassicaceae family, are consumed worldwide. Radish sprouts and young leaves are also cooked, preserved by salting or pickling, or eaten in salads. According to Vavilov *et al.* (1926), radish originated from the eastern Mediterranean region and Middle East, and the current varieties might have been domesticated in India and other parts of Asia. Radish has been cultivated in Korea and China since 400 BC (Kaneko and Matsuzawa, 1993; Kurina *et al.*, 2021; Vavilov *et al.*, 1926). Historical reports of radish kimchi date back to the Three Kingdoms era (700 BC) in Korea, and traditional radish recipes have been published in at least 11 Korean recipe books within the past 100 years (Cho, 2010). Radish is one of the most widely cultivated vegetables in Korea and has been professionally bred for "four-season cultivation".

In Asian countries, diverse varieties of radish are widely cultivated as large-rooted and long-season vegetables, whereas in the Americas and Europe, red, small-rooted, short-season radish varieties are cultivated. Black radish is used in salads in Spain because of its crispy texture, and in China, colorful radishes including 20-day red radish, green radish (green both outside and inside the root), and watermelon radish (green exterior and red interior) are consumed (Singh *et al.*, 2017; Vavilov *et al.*, 1926; Wang *et al.*, 2020). In contrast to the colorful radishes cultivated in China, white radishes with green shoulders have been preferred in Korea for a long time

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because there is a perception that these types of radishes, especially egg-shaped ones, are of higher quality, being sweet and crunchy. Most radish and *Brassica spp.* researches conducted in Korea have focused on cultivation and disease resistance (Afroz *et al*., 2021; Geum *et al*., 2021; Kim *et al*., 2020; Kwon *et al*., 2020; Rajalingam *et al*., 2021), with few studies conducted on the color and appearance of radish roots (Singh *et al*., 2017). However, color is one of the most important traits reflecting quality, and affects consumer preference.

Glucosinolates (GSLs) are sulfur-containing secondary metabolites considered as the main health-promoting (anti-cancer, antioxidant, and anti-inflammatory) compounds in most cruciferous vegetables (Barillari *et al*., 2005). GSLs have been reported in various species and cultivars, as well as in specific plant organs (Hwang *et al*., 2019; Jeon *et al*., 2018; Rhee *et al*., 2020). Glucoraphasatin (GRH), which is derived from glucoerucin (GER), is abundant in radish (Fahey *et al*., 2001; Ishida *et al*., 2015; Kakizaki *et al*., 2017). Rhee *et al*. (2020) assessed the GSL distribution across the inner, middle, and outer leaves of kimchi cabbage (*Brassica rapa* L.), and Jeon *et al*. (2018) evaluated the GSL content at different vegetative growth stages in *B. rapa* (Jeon *et al.,* 2018; Rhee *et al*., 2020). GSLs can be hydrolyzed by myrosinase to form breakdown products including isothiocyanates, which are responsible for the bitter taste of vegetables and exhibit cancer chemopreventive activity. Liu *et al*. (2018) compared nutritional values among different broccoli tissues and suggested various possible applications for broccoli by-products after analyzing sulforaphane derived from glucoraphanin (Liu *et al.*, 2018). GRH is hydrolyzed by myrosinase when plant cells are disrupted to produce raphasatin; when derived from GRH, raphasatin was reported to induce more potent detoxification enzymes than other degradation products (Scholl *et al*., 2011). Raphasatin exhibits chemopreventive effects, including some toxic effects on human breast adenocarcinoma cells (Scholl *et al*., 2011; Suzuki *et al*., 2016; 2017), in which it induces apoptosis (Ibrahim *et al*., 2018). Radish also converts isothiocyanates from GSLs more efficiently than broccoli (De Nicola *et al*., 2013), with the addition of radish sprouts to broccoli sprouts promoting sulforaphane formation in the latter (Liang *et al*., 2018). Therefore, it is important to identify radish varieties that produce large amounts of GSLs, as they can provide health benefits to humans.

Montaut *et al*. (2010) provide an excellent summary of GSL analytical methods (Montaut *et al.,* 2010). High-performance liquid chromatography (HPLC) has been used in many studies (Park *et al*., 2014) to analyze desulfated GSL with a UV-visible or photodiode array detector, but the desulfonation process is laborious, and some GSL may be insufficiently desulfonated at lower sulfatase concentrations. Recently, intact GSLs were identified and quantified using ultra-performance liquid chromatography (UPLC) with diode array detection-tandem mass spectrometry (MS/MS) in multiple reaction monitoring (MRM) mode (Gratacós-Cubarsí *et al*., 2010; Hwang *et al*., 2019). Several studies have analyzed GSL contents in the Brassicaceae family (Bhandari *et al*., 2015), but they often did not include GRH, which comprises 90% of all radish GSLs on average. Yi *et al*. (2016) investigated radish GSLs, but the numbers of germplasms and morphological traits analyzed were limited, and GSLs were analyzed in the form of desulfo-GSLs using HPLC (Yi *et al.*, 2016).

Large-scale characterization and evaluation of the agronomic traits and health-promoting chemicals in radish germplasms would help identify new germplasm breeding materials. Therefore, in this study, we aimed to profile GSLs and characterize the phenotypes of radish germplasms. We evaluated the GSL contents of 110 radish germplasms using liquid chromatography (LC)-MS/MS in MRM mode, and characterized qualitative and quantitative traits. The data from the correlation analysis could promote the exploitation of favorable traits by breeders, as well as diet diversification given the health benefits associated with various radish germplasms.

Materials and Methods

Plant cultivation and sample preparation

Seeds of 110 radish germplasms were obtained from the National Agrobiodiversity Center (Jeonju, Korea), and seeds of the following 10 Korean commercial cultivars were purchased from various companies: Gwailmu (Con1; Asia Seed Co., Seoul, Korea), Meosjinmaskkalmu (Con2; Nongwoobio., Suwon, Korea), Taecheong (Con3; Syngenta, Iksan, Korea), Cheongunmu (Con4; Farm Hannong, Seoul, Korea), Chorongmu (Con5;

Farm Hannong), Mansa-hyeongtongmu (Con6; Nongwoobio.), Togwanggoldeumu (Con7; Farm Hannong), Baeksinaltari (Con8; Koregon, Seoul, Korea), Syupeogiljomu (Con9; Nongwoobio.), and Seohogoldeumu (Con10; Nongwoobio.; Appendix 1).

The seeds were sown in an experimental field containing compost and fertilizer at the end of August 2017. Plants were cultivated in the field following cultural practices recommended by the Rural Development Administration. Fertilizer (N-P-K-Ca-B = 60-40-60-75-1.5 ㎏/10 a) was applied before the seeds were sown. Radishes were harvested at 3-10 weeks after sowing (at the optimal growth stage) for phenotypic characterization, and all root samples were freeze-dried (LP500 vacuum freeze-drier; Ilshinbiobase Co., Seoul, Korea) directly at -70℃ for 1 week. The samples were then ground into fine powder and stored at -20℃ until further analysis.

Characterization of phenotypic traits

Phenotypic traits were characterized at full maturity in the field. Radish leaves and roots were examined for 5 qualitative and 10 quantitative traits based on modified descriptors from the International Union for the Protection of New Varieties of Plants (UPOV, 2021) and reference descriptors for *Brassica* and *Raphanus* (IBPGR, 1990).

The five qualitative traits were radish root peel color, root shoulder color, root flesh color, root shape, and the extent of root burial in soil. The 10 quantitative traits were total weight (Twe), root length (RL), root width (Rwi), root length-to-width ratio (RR), root weight (Rwe), leaf length (LL), leaf width (Lwi), leaf length-to-width ratio (LR), leaf weight (Lwe), and leaf number (LN). Each characteristic was examined using a digital caliper and digital balance. Three to five independent biological samples were examined to characterize the quantitative and qualitative phenotypic traits.

Evaluation of glucosinolate contents

GSLs were extracted following the method reported by Rhee *et al*. (2020). GSLs were isolated from 100-mg freeze-dried samples using 1 mL of solvent (Methanol: deionized water = 80:20, v/v). Then, each mixture was vortexed and centrifuged at 16,000 rpm and 4℃ for 10 min. The supernatant was transferred into a new tube, re-centrifuged, filtered using a 0.45-㎛ syringe filter, and diluted 10 times before an internal standard solution was added. Finally, the filtered solution was transferred into a brown vial for further analysis. For this experiment, the internal standard was prepared using 100 ppb glucotropaeolin. We analyzed 18 GSL standards (Phytoplan Diehm & Neuberger GmbH; Heidelberg, Germany) using a Waters Acquity UPLC system (Waters, Milford, MA, USA) coupled with a Xevo TQ-S system (Waters MS Technologies, Manchester, UK) and finally selected the following five GSLs to evaluate the GSL contents in radish germplasms (Appendix 4): Glucoraphasatin (GRH), glucoraphenin (GRE), glucobrassicin (GBR), Glucoerucin (GER), and glucoberteroin (GBE). Glucotropaeolin was used as the internal standard to identify and quantify the GSLs in 110 germplasms and 10 commercial cultivars. Chromatographic separation was carried out using an Acquity UPLC BEH C_{18} (1.7 ㎛, 2.1 × 100 ㎜) column (Waters Corp., Manchester, UK). The flow rate was kept at 0.25 mL/min, the column temperature was maintained at 35℃, and the injection volume was 5 μL. The mobile phase comprised 0.1% trifluoroacetic acid in distilled water (A) and 0.1% trifluoroacetic acid in methanol (B). The UPLC gradient conditions were as follows: initial condition, 100% A; 0.0-1.0 min, 100% to 95% A; 1.0-4.0 min, 95% to 0% A; 4.0-4.5 min, 0% to 100% A; 4.5-5 min, 100% A; 5-15 min, 100% A. The mass spectrometry instrument was operated in negative ion electrospray ionization (ESI^-) and MRM modes. Data were acquired using MassLynx 4.1 software. GSLs were identified by comparing their retention times and MS and MS/MS fragmentation spectra with those of commercial standards. Each MRM transition was set as follows {compound name (retention time, parent molecular weight > daughter transition weight)}: GRH (5.18 min, 417 > 175.69), GRE (6.21 min, 433 > 418.5), GER (4.87 min, 419 > 177.71), GBE (6.21 min, 433 > 127.78), GBR (5.51 min, 446 > 204.69), and glucotropaeolin (4.75 min, 407 > 165.94). The final concentration of each GSL was calculated based on its curve area relative to that of the internal standard (glucotropaeolin) and linear regression equations derived from the calibration curve of the corresponding standard. The final concentrations of individual GSLs are presented in units of ㎍/g sample dry weight (DW).

Free-radical scavenging activity

To evaluate antioxidant activity in the radish germplasms, we modified the 2,2-diphenyl-1-picrylhydrazyl (DPPH) test protocol of Brand-Williams *et al.* (1995). DPPH powder (Sigma-Aldrich, St. Louis, MO, USA) was dissolved in 200 mL methanol to make a 150 mM DPPH solution, which was shaken in the dark for 1 h. Then, 1 mL of 80% methanol was added to each 2-mg freeze-dried sample, and the mixture was sonicated for 1 h and then centrifuged. The supernatant was analyzed for antioxidant activity. For the analysis, 150 ㎕ of 150 mM DPPH and 100 ㎕ of 2,000 ppm sample extract were mixed. DPPH solution and ascorbic acid (Sigma-Aldrich, Milwaukee, WI, USA) were used as a blank and standard, respectively. The absorbance at a wavelength of 517 ㎚ was measured. Experiments were performed in triplicate with independent germplasms. The free-radical scavenging activity was calculated as follows:

DPPH free-radical scavenging activity (%) =

$[1 - (A_{sample} - A_{sample\ blank}) / (A_{control} - A_{control\ blank})] \times 100\%$,

where A is the absorbance at 517 ㎚.

Statistical analysis

All experiments of GSL contents were conducted in technical triplicate, and the average ± standard deviation of GSL contents were calculated (㎍/g of root DW). Correlation analysis of the 10 phenotypic traits and individual and total compound amounts, as well as principal component analysis (PCA) of GSL contents and free-radical scavenging activities, were performed using XLSTAT software (Addinsoft, Paris, France). Analysis of variance followed by Duncan's multiple range test {least significant range (LSR), $p < 0.05$} was performed to determine if the content of each compound varied significantly by phenotypic traits. Student's t-test was done to identify significant-phenotypic differences between germplasms and cultivars.

Results

Phenotypic traits of radish root

In total, 15 phenotypic traits important for radish breeding were evaluated, including root color, shape, weight, and length. Five qualitative and ten quantitative traits of 110 radish germplasms and 10 Korean commercial cultivars were assessed (Appendix1 and 2), and the results are summarized in Table 1 and 2. Broad variation in all qualitative traits was observed in the radish germplasms compared to the commercial cultivars. In the latter, there was relatively little variation, especially in root peel color and root shoulder color. The root peel color of most germplasms (70.9%) and all cultivars (100%) was white. For the rest of the germplasms, two other root peel colors, bronze-green and red, were dominant. The radish germplasms produced roots with various root shoulder colors, including green (31.8%), whereas only the green shoulder color was observed in the cultivars. The root flesh color in the germplasm-produced roots and cultivars was mainly white (77.3% and 90%, respectively). Nineteen germplasms, but no

Table 1. Qualitative traits of 110 radish germplasms and 10 commercial cultivars, as evaluated using modified and reference UPOV (2021) and IBPGR (1990) descriptors, respectively, for *Brassica* and *Raphanus*

No.	Phenotypic traits	Description	Germplasms		Cultivars	
			n	%	n	%
1	Root peel color	Bronze-green	19	17.3	0	0
		Red	13	11.8	0	0
		White	78	70.9	10	100
2	Root shoulder color	Bronze-green	19	17.3	0	0
		Red	13	11.8	0	0
		Green	35	31.8	10	100
		White	43	39.1	0	0
3	Root fresh color	Red	6	5.5	1	10
		Green	19	17.3	0	0
		White	85	77.3	9	90
4	Root shape	Almond	5	4.5	0	0
		Ovate	13	11.6	0	0
		Gourd	1	0.9	2	20
		Narrow rectangle	35	31.8	0	0
		Elliptic	4	3.6	7	70
		Rectangle	19	17.3	0	0
		Spheerical	21	19.1	0	0
		Transverse elliptic	4	3.6	0	0
		Broad rectangle	8	7.3	1	10
5	Root position in soil	Above	6	5.5	0	0
		Mostly above	19	17.3	1	10
		Half buried	34	30.9	6	60
		Mostly buried	51	46.4	3	30
		Sum	110		10	

cultivars, produced roots with green flesh. The germplasms produced various root shapes, such as a narrow rectangle (31.8%), sphere (19.1%), and rectangle (17.3%), whereas the roots of the cultivars were mostly elliptical (70%) or gourd-shaped (20%). Regarding the root position in soil, germplasm-produced roots were mostly buried (46.4%) or half buried (30.9%), whereas most cultivar-produced roots were half buried in soil (60%).

Quantitative traits were more variable in the radish germplasms compared to the cultivars, especially Twe, Rwe, Lwe, RL, LL, Rwi, Lwi, RR, LR, and LN (Table 2). The average Twe of the cultivars was higher (2,088.9 g) than that of the germplasms (1,827.5 g), as was the average Rwe (1,753.3 vs. 1,286.3 g). Conversely, the average Lwe of the germplasms was higher (541.1 g) than that of the cultivars (335.3 g), and the average RL and LL were greater in the germplasms (24.1 and 45.6 ㎝, respectively) than in the cultivars (20.6 and 39.9 ㎝, respectively), despite the average Rwi (11.8 vs. 10 ㎝) and Rwe being greater in the latter. Both Rwe and Lwe were significantly different between germplasms and cultivars ($p < 0.05$) in Table 2. Leaves derived from the germplasms were wider (average width, 16.7 ㎝) than in the cultivars (average, 15.9 ㎝), but the LR was similar between the germplasms (2.8) and cultivars (2.5). For the RR, there was a marked difference between the germplasms (2.7) and cultivars (1.7). The numerical difference in the ratio was small, but the RR range of the germplasms was much broader than that of the cultivars. The average LN was similar between the germplasms (26.5) and cultivars (25.1), with the former having a broader range (8.7-59) compared to the latter (19-33).

Glucosinolate contents of radish roots

The total GSL content and content of each of the five individual GSLs examined in the radish germplasms and cultivars (Appendix 3) are summarized in Table 3. The average total GSL content in the germplasm-produced roots was 7,535.7 ㎍/g DW. The average content of GRH, the main constituent (73.2%) of the total GSL content in radish, was 5,512.9 ㎍/g DW. The GRH content also varied the most widely among the five GSLs (123.8-12,922.0 ㎍/g DW). The average contents of GRE, GER, GBR, and GBE in the germplasm-produced roots were 1,716.9, 165.8, 127.1, and 12.9 ㎍/g DW, respectively. The GBE, GBR and GER contents did not differ significantly from each other, whereas the GRE, GRH, and total GSL contents differed significantly from the contents of the other constituents (Duncan's LSR, $p < 0.05$). The GBE, GBR, GER, and GRE contents were similar to each other in the cultivar-produced roots, whereas the GRH and total GSL contents were significantly different from the contents of the other constituents (Duncan's LSR, $p < 0.05$). The GRE

Table 2. Quantitative traits of 110 radish germplasms and 10 commercial cultivars. Total weight was calculated as the sum of root weight and leaf weight. The root and leaf ratios are the ratios of root length (㎝) to root width (㎝) and leaf length (㎝) to leaf width (㎝), respectively

No.	Phenotypic traits	Germplasms			Cultivars		
		Range	Median	Average ± SD[z]	Range	Median	Average ± SD[z]
1	Total weight (Twe; g)	45.4 - 3420.0	1799.1	1827.5 ± 637.8	723.3 - 2776.7	2113.3	2088.7 ± 621.2
2	Root weight (Rwe; g)*[y]	45.0 - 2918.3	1280.0	1286.3 ± 463.8	588.3 - 2363.3	1948.3	1753.3 ± 529.4
3	Leaf weight (Lwe; g)*[y]	0.4 - 1833.3	515.2	541.1 ± 279.0	135.0 - 575	363.3	335.3 ± 129.5
4	Root length (RL; ㎝)	2.5 - 48.0	23.2	24.1 ± 10.8	12.0 - 25.8	21.2	20.6 ± 4.6
5	Root width (RW; ㎝)	2.1 - 41.8	9.6	10.0 ± 3.8	10.5 - 12.6	11.8	11.8 ± 0.6
6	Leaf length (LL; ㎝)	14.2 - 62.0	46.8	45.6 ± 8.9	32.3 - 48.3	38.5	39.9 ± 4.6
7	Leaf width (LW; ㎝)	8.4 - 25.8	17.1	16.7 ± 3.3	11.8 - 18.9	17.3	15.9 ± 2.3
8	Root ratio (RR; len/wid)	0.7 - 6.2	2.3	2.7 ± 1.5	1.1 - 2.1	1.9	1.7 ± 0.3
9	Leaf ratio (LR; len/wid)	1.7 - 4.1	2.8	2.8 ± 0.5	2.0 - 3.1	2.5	2.5 ± 0.4
10	Leaf number (LN)	8.7 - 59.0	25.3	26.5 ± 11.0	19.0 - 33.0	25.4	25.1 ± 4.4

[z]SD means standard deviation, [y]Asterisk indicates significant differences in each quantitative trait between germplasms and cultivars (t-test, $p < 0.05$).

Table 3. Contents of total glucosinolates (GSLs) and five GSLs in the germplasms and cultivars with the highest contents, mean total and individual GSL contents, and the range of values for each GSL type (㎍/g DW). GSLs contents were analyzed using liquid chromatography-tandem mass spectroscopy in multiple reaction monitoring mode, with glucotropaeolin as the internal standard

	110 germplasms			10 commercial varieties		
	Average	Range	Top germplasm	Average	Range	Top variety
Total glucosinolate content	7535.7d[y]	154.3 - 18438.5	299453	7989.6c[y]	4093.5 - 10873.1	Seohogoldeumu
Glucoraphasatin	5512.9c[y]	123.8 - 12922.0	215011	6794b[y]	2531.3 - 9247	Seohogoldeumu
Glucoraphenin*[z]	1716.9b[y]	26.3 - 5653.2	306869	956.8a[y]	509.6 - 1307.1	Syupeogiljomu
Glucoerucin	165.8a[y]	2.4 - 534.5	299453	155.4a[y]	40.9 - 292.9	Gwailmu
Glucobrassicin	127.1a[y]	0.7 - 1243.9	306869	73.6a[y]	7.9 - 268.4	Seohogoldeumu
Glucoberteroin*[z]	12.9a[y]	0 (ND) - 59.1	299453	9.8a[y]	4.7 - 17.3	Seohogoldeumu

[z]Asterisk indicates significant differences in the content of a given compound between germplasms and cultivars (t-test, $p < 0.05$). [y]Different characters indicate significant differences in mean content (Duncan's multiple comparison test, $p < 0.05$) for each germplasm or cultivar. The glucoraphenin and glucoberteroin contents differed significantly between germplasms and cultivars. No significant differences were found for the other GSLs.

and GBE contents were significantly different between germplasm-and cultivar-produced roots (Student's t-test, $p < 0.05$) in Table 3.

The roots of the following germplasms contained the highest amounts of the specified GSLs (Table 3): IT215011, GRH; IT306869, GRE and GBR; IT299453, GER and GBE. Among the 10 cultivars, Seohogoldeumu had the highest total GSL content (and the highest GRH, GBR, and GBE contents), while Syupeogiljomu had the highest GRE content and Gwailmu had the highest GER content. The content range for all GSLs was broader in germplasm-produced roots than Korean cultivar-produced roots.

Correlation analysis of phenotypic traits and glucosinolate profiles

Correlation analysis of the 15 phenotypic traits and contents of the individual GSLs was performed using XLSTAT software. The Pearson correlation coefficients are presented in Table 4. Twe, which was calculated by summing Rwe and Lwe, was more strongly correlated with Rwe (r = 0.916) than with Lwe (r = 0.725). Twe was also significantly correlated with LL (r = 0.651), RL (r = 0.580), and LN (r = 0.529). Rwe was significantly correlated with RL (r = 0.585), and Lwe was significantly correlated with LL (r = 0.684) and LN (r = 0.629). The RR was more strongly correlated with RL (r = 0.918) than with Rwi (r = -0.463). The RL was negatively correlated with DPPH antioxidant scavenging capacity (r = -0.431). LL was significantly correlated with Lwi (r = 0.678).

In Table 4, GRH was significantly correlated with the other GSLs, except GBR. GRH, the most abundant GSL in radish root, was highly correlated with the total GSL content (r = 0.984) and GER (r = 0.938). The strongest correlation among the five GSLs was observed between GRH and GER (r = 0.938), in accordance with previous reports. GRH was also strongly correlated with GBE (r = 0.858) and GRE (r = 0.755). GER (r = 0.934) and GBE (r = 0.878) were more strongly correlated with the total GSL content than was GRE (r = 0.755). GBR had weaker correlations with the other GSLs but was the only GSL positively correlated with DPPH anti-oxidant scavenging (r = 0.166).

Principal component analysis

Principal component analysis was conducted to analyze the relationships among GSL profiles (total GSL content, GRH, GBR, GER, GBE, and GRE) and antioxidant activity (DPPH scavenging) in the 110 radish germplasms (Fig. 1). The first two principal components (F1 and F2), represented as the x- and y-axis in the PCA biplot (Fig. 1), explained 68.88% and 15.97% (sum, 84.85%) of the total variance, respectively.

Five components, namely the total GSL content (20.1%), GRH (18.8%), GER (18.5%), GBE (17.8%), and GRE (15.9%), were the main contributors to F1, whereas DPPH activity (78.8%) and GBR (17.5%) were the main contributors to F2. The six GSL components had positive loadings on F1, with

Table 4. Pearson correlation analysis of 10 phenotypic traits and the contents of six GSLs (plus the total GSL content) in 110 germplasms using a range-scaled data set (the minimum and maximum values of normalized data for all traits are 0 and 1, respectively)

Traits	Twe^{z}	Rwe	Lwe	RL	Rwi	RR	LL	Lwi	LR	LN	GRH	GRE	GBR	GER	GBE	TG
Rwe^{y}	**0.92^{**g}**															
Lwe^{x}	**0.73^{**g}**	0.39^{**g}														
RL^{w}	**0.58^{**g}**	**0.59^{**g}**	0.33^{**g}													
Rwi^{v}	0.32^{**g}	0.37^{**g}	0.11	-0.16												
RR^{u}	0.33^{**g}	0.28^{**g}	0.28^{**g}	**0.92^{**g}**	-0.46^{**g}											
LL^{t}	**0.65^{**g}**	0.47^{**g}	**0.68^{**g}**	0.14	0.30^{**g}	0.01										
Lwi^{s}	0.48^{**g}	0.35^{**g}	0.49^{**g}	0.07	0.23^{*h}	-0.02	**0.68^{**g}**									
LR^{r}	0.25^{**g}	0.18	0.26^{**g}	0.10	0.11	0.03	0.45^{**g}	-0.33**								
LN^{q}	**0.53^{**g}**	0.34^{**g}	**0.63^{**g}**	0.45^{**g}	-0.05	0.42^{**g}	0.25^{**g}	-0.06	0.38^{**g}							
GRH^{p}	0.35^{**g}	0.30^{**g}	0.29^{**g}	0.21^{*h}	0.07	0.16	0.27^{**g}	0.18	0.13	0.22^{*h}						
GRE^{o}	0.18	0.23^{*h}	0.02	0.06	0.17	-0.02	0.17	0.16	0.04	-0.13	**0.76^{**g}**					
GBR^{m}	-0.11	-0.09	-0.10	-0.20^{*h}	0.06	-0.17	0.07	0.08	0.02	-0.13	0.49^{***f}	**0.59^{**g}**				
GER^{l}	0.32^{**g}	0.31^{**g}	0.20^{*h}	0.23^{*h}	0.06	0.17	0.19^{*h}	0.10	0.12	0.20^{*h}	**0.94^{**g}**	**0.74^{**g}**	0.49^{**g}			
GBE^{k}	0.18	0.17	0.11	0.12	0.03	0.11	0.20^{*h}	0.14	0.10	0.01	**0.86^{**g}**	**0.76^{**g}**	**0.55^{**g}**	**0.89^{**g}**		
TG^{j}	0.31^{**g}	0.29^{**g}	0.23^{*h}	0.17	0.10	0.12	0.25^{**g}	0.18	0.11	0.13	**0.98^{**g}**	**0.86^{**g}**	**0.57^{**g}**	**0.93^{**g}**	**0.88^{**g}**	
DPPH^{i}	-0.39^{**g}	-0.35^{**g}	-0.29^{**g}	-0.43^{**g}	-0.03	-0.38^{**g}	-0.26^{**g}	-0.17	-0.16	-0.28^{**g}	-0.10	-0.01	0.17	-0.15	-0.10	-0.08

Bold characters: $r > 0.6$, $p < 0.01$. ^{z}Twe: total weight (g), ^{y}Rwe: root weight (g), ^{x}Lwe: leaf weight (g), ^{w}RL: root length (㎝), ^{v}Rwi: root width (㎝), ^{u}RR: root length-to-width ratio, ^{t}LL: leaf length (㎝), ^{s}Lwi: leaf width (㎝), ^{r}LR: leaf length-to-width ratio, ^{q}LN: leaf number, ^{p}GRH: glucoraphasatin, ^{o}GRE: glucoraphenin, ^{m}GBR: glucobrassicin, ^{l}GER: glucoerucin, ^{k}GBE: glucoberteroin, ^{j}TG: total GSL content, including GRH, GRE, GBR, GER, and GBE, ^{i}DPPH: 2,2-diphenyl-1-picrylhydrazyl. ^{h}*, ^{g}** and ^{f}*** indicate significant correlations between two traits at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

the total GSL content and GRH having the highest loadings, whereas DPPH activity was negatively loaded. DPPH activity, GBR, and GRE had positive loadings on F2, and the total GSL content, GBE, GRH, and GER had negative loadings (Fig. 1).

Based on their location in the PCA plot, the GSL contents may share some common tendencies. Along F1, more positive values reflect higher total GSL, GRH, GER, GBE, and GRE contents, and vice versa. These components do not make a large contribution to F2. More positive values for both F1 and F2 reflect higher GBR content. When the F1 value is positive and the F2 value is negative, the GBR content is low. When the F1 value is negative, the GBR content is intermediate. A negative F1 value and positive F2 value reflects high DPPH activity. In contrast to F2, DPPH activity does make a large contribution to F1, so observations located in the upper half of the plot indicate high DPPH activities and vice versa.

In the PCA biplot, the 110 germplasms were separated into five groups (Fig. 1). Group I (circled in red) contains five radish germplasms (4.5%) and is located in the upper right quadrant between +3.9 and +6.5 on the F1 axis and -0.4 and +2.8 on the F2 axis. The germplasms in Group I had > 10,000 ㎍/g DW GRH, > 15,000 ㎍/g DW for the total GSL content, > 100 ㎍/g DW GBR, and relatively high total GSL and GRH contents compared to the other groups. Two accessions, IT299453 (No. 104) and IT306869 (No. 107), had high total GSL content (18,438 and 18,018 ㎍/g, respectively) but exhibited low and moderate levels of DPPH activity, respectively. IT299453 (No. 104) was also located below IT306869 (No. 107). The IT215011 (No. 36) germplasm had the highest GRH content (12,922 ㎍/g DW) but only a moderate GBR content, and also exhibited moderate DPPH activity. It is positioned on the left side (negative F2) of the plot. Both IT306869 (No. 107) and IT215011 (No. 36) had high total GSL and GRH contents,

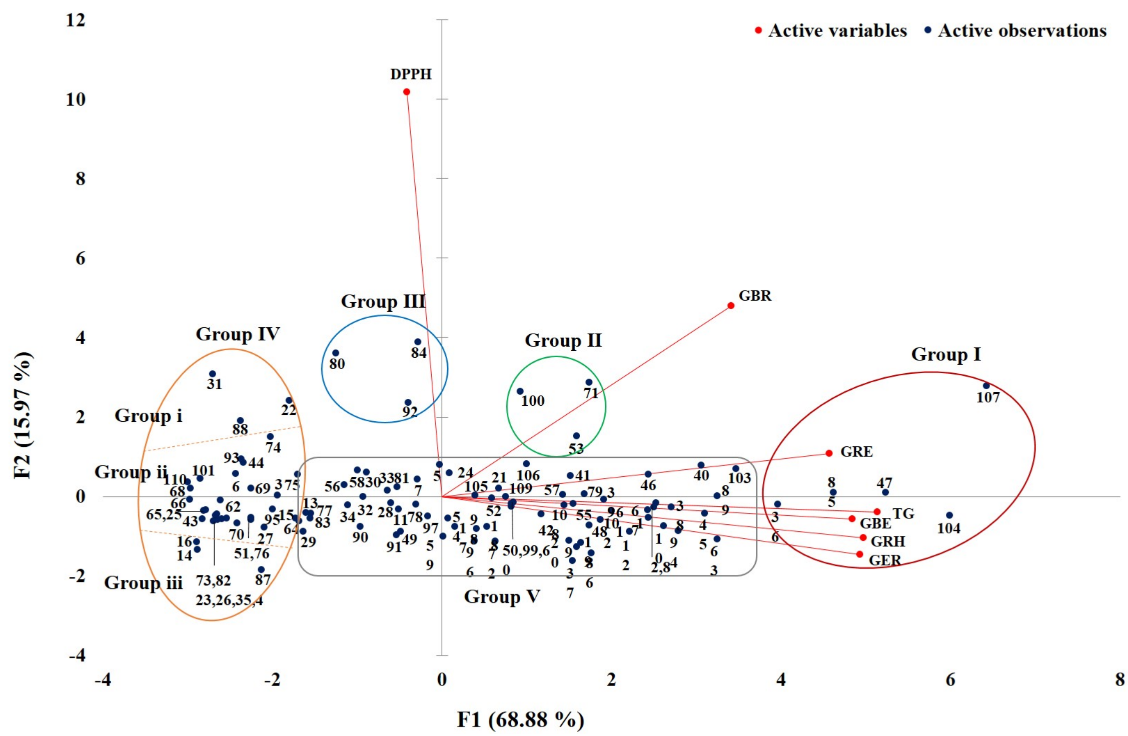


Fig. 1. Principal component analysis (PCA) biplot of root samples produced by 110 radish germplasms based on glucosinolate (GSL) contents and quantitative antioxidant activity. GRH: glucoraphasatin, GRE: glucoraphenin, GER: glucoerucin, GBR: glucobrassicin, GBE: glucoberteroin, TG: total GSL content, DPPH: antioxidant activity.

with moderate levels of DPPH activity.

Group II contains three radish germplasms (2.7%) and is located in the upper right quadrant of the plot, within +0.9 to +1.7 on the F1 axis and +1.5 to +2.8 on the F2 axis (Fig. 1). The germplasms in Group II had total GSL contents of > 9,500 ㎍/g DW and antioxidant activities of > 40%. The GRE and GBR contents were moderate to high. The GSL contents were lower compared to Group I, but the antioxidant activities were higher. Of the three germplasms, IT262036 (No. 71) had the highest GBR content (533.3 ㎍/g DW), and its position indicates an association with GBR-related variables. IT297120 (No. 100) also had a high GBR content (449.1 ㎍/g DW), but its total GSL content was low (although its DPPH activity was still high). IT250790 (No. 53) had a high GRE content (4,421.2 ㎍/g DW).

Group III contains three germplasms and is located within -1.3 to -0.2 on the F1 axis and +2.3 to +3.9 on the F2 axis (Fig. 1). The germplasms in Group III exhibited high antioxidant activities (> 40%, with the highest activity level being 63.1%), moderate-to-low GSL contents, and high GBR contents (> 100 ㎍/g DW). Of the three germplasms, IT264178 (No. 80) exhibited the highest DPPH antioxidant activity but had a low GSL content; IT278682 (No. 84) had the highest GBR content (591.2 ㎍/g) in the group.

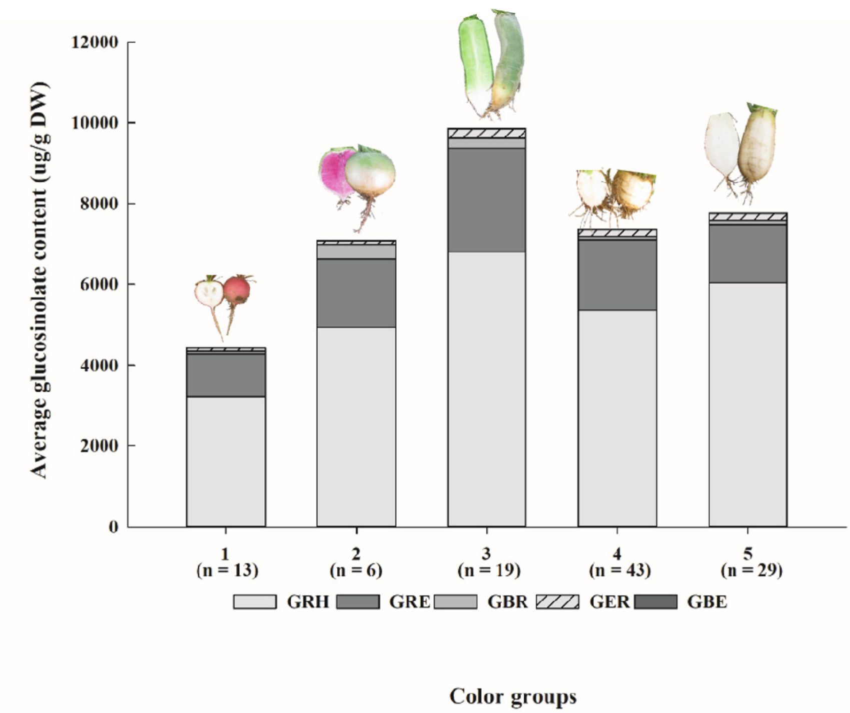
Group IV contains 34 germplasms, and is located within -3 to -1.7 on the F1 axis and -1.8 to +3.0 on the F2 axis (Fig. 1). Group IV members had low individual and total GSL contents. Group IV was further divided into three subgroups (Groups i-iii) with 3, 28, and 3 accessions, respectively, according to the antioxidant activity level. Group i members exhibited the highest antioxidant activities (> 45%), followed by Group ii (15-38%) and Group iii members (< 13%). The antioxidant activity levels in Group i were high, although the GSL contents were not. IT278727 (No. 88), IT136498 (No. 22), and IT208400 (No. 31) produced radish roots with red peel. IT208400 (No. 31) exhibited the highest antioxidant activity (59.8%) despite having a low total GSL content (1,334 ㎍/g DW). Group ii members had low GSL contents and exhibited largely similar levels of antioxidant activity. Group iii members {IT103811 (No. 14), IT112253 (No. 16), and IT278685 (No. 87)} exhibited the lowest antioxidant activities (< 13%) and did not produce red roots. IT278685 (No. 87) exhibited the lowest antioxidant activity (4.3%) and had the lowest GSL content.

Group V is positioned in the center of the plot, within -1.7 to +3.5 on both the F1 and F2 axis, and contains 65 germplasms (Fig. 1). No individual traits obviously characterized the group members, and the values of most traits were in the moderate range. To distinguish this group more precisely, more traits need to be analyzed.

Glucosinolate contents of root color-based groups

We classified radish germplasms based on their root color phenotypes, as follows: color group 1, red peel with a red shoulder and white flesh; color group 2, white peel with a green shoulder and red flesh; color group 3, bronze-green peel and shoulder with green flesh; color group 4, white peel, shoulder, and flesh (totally white); and color group 5, white peel with a green shoulder and white flesh (Fig. 2).

Color group 1 included 13 germplasms with a mean total GSL content of 4,424.2 ㎍/g DW (range: 642.0-13,044.0 ㎍/g



	Color groups				
	1	2	3	4	5
TG[z]	4424.2a[t]	7082.3ab[t]	9864.9b[t]	7356.2ab[t]	7764.3ab[t]
GRH[y]	3214.3a[t]	4928.7ab[t]	6807.1b[t]	5361.1ab[t]	6041.3b[t]
GRE[x]	1061a[t]	1690.7ab[t]	2560.2b[t]	1732.7ab[t]	1440.4a[t]
GBR[w]	62.4a[t]	364.9b[t]	253.9b[t]	79.0a[t]	95.2a[t]
GER[v]	81.1a[t]	90.8ab[t]	219.7b[t]	172ab[t]	174.8ab[t]
GBE[u]	5.2a[t]	7.2a[t]	24.0b[t]	11.4a[t]	12.6a[t]

Fig. 2. Radish germplasms grouped depending on root colors. Top: The pictures show the exterior and interior of roots containing the highest levels of GSLs for each color group (Nos. 12, 71, 104, 107, and 36). Bottom: The mean total and individual GSL contents in the five color groups. The total (TG) and individual GSL contents and DPPH activity were assessed in multiple comparison tests (Duncan's least significant range test) to determine if the differences between pairs of color groups were significant ($p < 0.05$). [z]TG: total GSL content, [y]GRH: glucoraphasatin, [x]GRE: glucoraphenin, [v]GER: glucoerucin, [w]GBR: glucobrassicin, [u]GBE: glucoberteroin. [t]Different characters mean statistically significance.

DW; Fig. 2), which was the lowest mean content among all color groups. Color group 2 included six germplasms with a mean total GSL content of 7,082.3 ㎍/g DW (range: 2,660.9-11,859.5 ㎍/g DW). Color group 3 included 19 germplasms with a mean total GSL content of 9,864.9 ㎍/g DW (range: 1,532.8-18,438.5 ㎍/g DW), which was the highest mean content among all color groups. Color group 4 included 43 germplasms with a mean total GSL content of 7,356.2 ㎍/g DW (range: 154.3-18,017.9 ㎍/g DW), and color group 5 included 29 germplasms with a mean total GSL content of 7,764.3 ㎍/g DW (range: 274.4-16,073.8 ㎍/g DW).

Images above the bar graph show the exterior and interior of the roots in each group with the highest GSL contents (IT102560, IT262036, IT299453, IT306869, and IT215011). In color group 1, the mean GRH, GRE, GBR, GER, and GBE contents were, respectively, 3,214.3, 10,613, 62.43, 81.13, and 5.23 ㎍/g DW, comprising 72.7%, 24%, 1.4%, 1.8%, and 0.1% of the total GSL content. Of the five color groups, group 1 germplasms had the lowest individual GSL contents, but the antioxidant activity was not as low. We further divided this group into two subgroups based on a root weight cutoff of 250 g. Of 13 germplasms, four weighed less than 250 g; these small radishes are eaten in salads or as pickles in Europe and the United States. The small radishes had lower GSL contents compared to the bigger radishes, but the antioxidant activities were high.

In color group 2, the mean GRH, GRE, GBR, GER, and GBE contents were, respectively, 4,928.7, 1,690.7, 364.9, 90.8, and 7.2 ㎍/g DW, comprising 69.6%, 23.9%, 5.2%, 1.3%, and 0.1% of the total GSL content (Fig. 2). The GBR content was significantly higher than in the other groups, and the mean antioxidant activity was the highest. In color group 3, the mean GRH, GRE, GBR, GER, and GBE contents were, respectively, 6,807.1, 2,560.2, 253.9, 219.7, and 24 ㎍/g DW, comprising 69%, 26%, 2.6%, 2.2%, and 0.2% of the total GSL content. The individual GSL contents were significantly higher than in the other groups, but unexpectedly, the mean antioxidant activity (DPPH free-radical scavenging activity) was not high.

In color group 4, the mean GRH, GRE, GBR, GER, and GBE contents were, respectively, 5,361.1, 1,732.7, 95.2, 172, and 11.4 ㎍/g DW, comprising 72.9%, 23.6%, 1.1%, 2.3%, and 0.2% of the total GSL content. In color group 5, the mean GRH, GRE, GBR, GER, and GBE contents were, respectively, 6,041.3, 1,440.4, 95.2, 174.8, and 12.6 ㎍/g DW, comprising 77.8%, 18.6%, 1.2%, 2.3%, and 0.2% of the total GSL content (7,764.3 ㎍/g DW). Radishes belong to this group are known as kimchi radishes and are particularly preferred in Korea.

Discussion

We found that various phenotypic traits were highly correlated with each other. In cases where desirable and undesirable traits are highly correlated, breeding programs employ selection processes to uncouple the correlations. According to Jatoi *et al*. (2011), Twe was highly correlated with Lwi (r = 0.70) and RL (r = 0.71) in their radish samples. In this study, we observed a significant correlation between Twe and LL (r = 0.65), as did Jatoi *et al*. (2011). Color is an important external characteristic used to evaluate radish quality. Customers in Korea prefer white radishes with green shoulders. This type of radish has a sweet taste and crispy texture, and is popularly used to make kimchi, a traditional Korean side dish, along with soups and various other side dishes. Consumers often modify their dietary habits to improve health. This could explain the recent increase in popularity of food products derived from *Brassica* vegetables, and the development of experimental products such as broccoli puree with lactic acid (Cai *et al*., 2019) and muffins enriched with dietary fiber from kimchi (Heo *et al*., 2019). *Brassica* plants contain GSLs that can be degraded by intestinal microorganisms to produce bioactive metabolites such as isothiocyanates, which have anti-cancer and other biological properties (Aires *et al*., 2009). In this study, five GSLs, four aliphatic GSLs (GER, GRH, GRE, and GBE) and one indole GSL (GBR) were screened and quantified in 110 radish germplasms. Three aliphatic GSLs (GRH, GER, and GBE) were significantly correlated with one another but not with GBE or the indole GSL, GBR. This could be due to differences in biosynthetic pathways and precursors, with GRH, GER, and GBE sharing a similar 4C pathway, whereas GBE is derived from a 5C pathway. GBR, the indole GSL, has a different amino-acid precursor, tryptophan.

The GSL contents in radish were found to be correlated with some phenotypic traits. The total GSL content was significantly correlated with LL but not with RL. A similar observation was reported for kimchi cabbage by Jeon *et al*. (2018) and Kakizaki *et al*. (2017), who studied the synthesis and movement of GSL (Jeon *et al*., 2018; Kakizaki *et al*., 2017). Yi *et al*. (2016) reported no strong correlations among root shape, pithiness, sweetness, peel color, length, and GSL content (Yi *et al*., 2016). Root phenotypic characters such as color, shape, and length were not strongly associated with the GSL profile of the radish germplasms in this study, implying that the root phenotype does not reflect GSL contents. However, based on this finding, it may be possible to develop radish varieties of various phenotypes with high GSL contents.

According to our PCA, GSL contents were not strongly correlated with DPPH activity. Raphasatin, a degradation product of GRH, was reported to more potently induce detoxification enzymes than other degradation products (Scholl *et al*., 2011; Suzuki *et al*., 2016). A more complete understanding of the overall antioxidant effect could be achieved by measuring the antioxidant activities of isothiocyanates such as raphasatin. The germplasms in Group III in the PCA plot in Fig. 1 produce small red radishes with high DPPH free-radical scavenging activities. To determine whether the antioxidant effect is influenced by the root size or red pigment, small non-red radish germplasms can be analyzed. Red radishes contain higher levels of high anthocyanins and other phenolic compounds than non-pigmented radishes (Singh *et al*., 2017). Hence, they can be used to prepare healthful, nutrient-dense dishes and nutraceutical formulations.

In this study, we assessed various phenotypic traits, DPPH free-radical scavenging activity, and the contents of five GSLs in radish germplasms. The results regarding GSL levels in radishes, and their relationships with leaf and root characteristics, could be used as baseline data by breeders and nutraceutical companies. Moreover, the biochemical and phenotypic information provided by this study may encourage consumers to diversify their eating habits.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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Appendix 1. Qualitative phenotype characters of 110 germplasms and 10 Korean cultivars

No.	IT No.	Root peel color	Root shoulder color	Root fresh color	Root shape	Root position in soil
1	32729	White	Green	White	N-rectangle	Half B
2	100590	White	Green	White	Rectangle	Half B
3	100649	White	Green	White	N-rectangle	Half B
4	100678	White	Green	White	Rectangle	Mostly B
5	100684	White	Green	White	Almond	Mostly B
6	100689	White	Green	White	Egg	Half B
7	100691	White	Green	White	Rectangle	Mostly B
8	100695	White	Green	White	Rectangle	Half B
9	102376	White	Green	White	N-rectangle	Mostly B
10	102378	White	Green	White	N-rectangle	Half B
11	102395	White	Green	White	N-rectangle	Half B
12	102560	Red	Red	White	Egg	Half B
13	103802	White	Green	White	Rectangle	Mostly B
14	103811	White	Green	White	Oval	Mostly B
15	104055	White	Green	White	W-rectangle	Mostly B
16	112253	White	White	White	N-rectangle	Mostly B
17	112255	White	White	White	N-rectangle	Mostly B
18	112257	White	White	White	N-rectangle	Mostly B
19	112258	White	White	White	N-rectangle	Mostly B
20	119000	White	Green	White	Rectangle	Mostly B
21	136485	White	White	White	N-rectangle	Mostly B
22	136498	Red	Red	White	Spherical	Mostly A
23	166993	White	White	White	Rectangle	Mostly B
24	166995	White	White	White	N-rectangle	Half B
25	166997	White	White	White	N-rectangle	Mostly B
26	185738	White	Green	White	Egg	Mostly B
27	188102	Bronze-green	Bronze-green	Green	W-rectangle	Mostly A
28	203316	Bronze-green	Bronze-green	Green	W-Oval	Mostly A
29	203531	White	Green	White	Rectangle	Mostly B
30	204160	White	Green	White	Rectangle	Mostly B
31	208400	Red	Red	White	Egg	Mostly A
32	209937	Bronze-green	Bronze-green	Green	Egg	Mostly A
33	209974	White	White	White	N-rectangle	Half B
34	210203	White	White	White	N-rectangle	Mostly B
35	213153	White	Green	White	Egg	Mostly B
36	215011	White	Green	White	Gourd	Mostly B
37	215079	White	White	White	N-rectangle	Half B
38	218925	White	Green	White	Egg	Mostly B
39	220675	Bronze-green	Bronze-green	Green	Egg	Mostly A
40	221952	Bronze-green	Bronze-green	Green	Rectangle	Mostly A
41	221955	White	White	White	Almond	Mostly B

Appendix 1. Continued

No.	IT No.	Root peel color	Root shoulder color	Root fresh color	Root shape	Root position in soil
42	221956	White	White	White	Almond	Mostly B
43	221958	White	White	White	Almond	Half B
44	221959	White	White	White	Rectangle	Half B
45	223576	Bronze-green	Bronze-green	Green	W-rectangle	Above
46	228857	Bronze-green	Bronze-green	Green	Egg	Above
47	228870	Bronze-green	Bronze-green	Green	Spherical	Above
48	250738	White	White	White	N-rectangle	Mostly B
49	250765	White	White	White	N-rectangle	Mostly B
50	250775	Bronze-green	Bronze-green	Green	Spherical	Above
51	250777	Bronze-green	Bronze-green	Green	Egg	Above
52	250788	White	White	White	N-rectangle	Mostly B
53	250790	White	White	White	W-rectangle	Mostly B
54	250792	Bronze-green	Bronze-green	Green	Rectangle	Mostly A
55	250794	Bronze-green	Bronze-green	Green	Rectangle	Mostly A
56	261944	Red	Red	White	Spherical	Half B
57	261947	White	White	White	N-rectangle	Half B
58	261953	White	White	White	Spherical	Half B
59	261954	White	Green	White	N-rectangle	Mostly B
60	261955	Bronze-green	Bronze-green	Green	N-rectangle	Mostly A
61	261967	White	White	White	N-rectangle	Mostly B
62	261978	Red	Red	White	Spherical	Half B
63	261989	White	White	White	N-rectangle	Mostly B
64	261995	White	White	White	N-rectangle	Half B
65	262006	White	White	White	Egg	Mostly B
66	262018	White	White	White	Rectangle	Mostly B
67	262022	White	White	White	N-rectangle	Mostly B
68	262023	White	White	White	W-rectangle	Half B
69	262031	Red	Red	White	Spherical	Half B
70	262032	Bronze-green	Bronze-green	Green	W-rectangle	Above
71	262036	White	Green	Red	Spherical	Half B
72	262037	White	White	White	N-rectangle	Mostly B
73	262044	White	White	White	Almond	Half B
74	262049	White	Green	Red	Spherical	Half B
75	262050	Red	Red	White	W-Oval	Half B
76	262057	White	Green	White	Oval	Mostly B
77	262070	Red	Red	White	W-Oval	Half B
78	262075	White	White	White	Spherical	Half B
79	262076	White	White	White	Spherical	Mostly B
80	264178	White	Green	Red	Spherical	Half B
81	264180	White	White	White	Spherical	Mostly B
82	276165	White	White	White	N-rectangle	Mostly A

Appendix 1. Continued

No.	IT No.	Root peel color	Root shoulder color	Root fresh color	Root shape	Root position in soil
83	278269	White	White	White	W-rectangle	Mostly B
84	278682	White	Green	Red	W-rectangle	Half B
85	278683	Bronze-green	Bronze-green	Green	N-rectangle	Mostly A
86	278684	White	White	White	N-rectangle	Mostly A
87	278685	White	White	White	N-rectangle	Mostly B
88	278727	Red	Red	White	Spherical	Mostly A
89	283305	White	White	White	Spherical	Mostly B
90	283312	White	Green	White	N-rectangle	Mostly B
91	283317	Red	Red	White	Spherical	Half B
92	289244	White	Green	Red	Spherical	Half B
93	291383	Red	Red	White	Egg	Half B
94	291423	White	Green	White	Oval	Mostly B
95	291541	White	White	White	Rectangle	Mostly B
96	293006	White	White	White	Spherical	Mostly B
97	293008	White	Green	White	N-rectangle	Mostly B
98	293028	White	Green	White	Egg	Mostly B
99	293085	White	Green	White	Oval	Mostly B
100	297120	White	Green	Red	Spherical	Half B
101	297172	Red	Red	White	Spherical	Mostly A
102	297174	White	White	White	Rectangle	Mostly B
103	299326	Bronze-green	Bronze-green	Green	N-rectangle	Mostly A
104	299453	Bronze-green	Bronze-green	Green	N-rectangle	Mostly A
105	305085	White	Green	White	Rectangle	Half B
106	305381	Bronze	Bronze-green	Green	Rectangle	Mostly A
107	306869	White	White	White	W-Oval	Mostly B
108	308359	Red	Red	White	Spherical	Half B
109	308367	Bronze-green	Bronze-green	Green	Rectangle	Mostly A
110	308418	White	White	White	N-rectangle	Mostly B
Con1	Gwailmu	White	Green	Red	W-rectangle	Half B
Con2	Meosjinmaskkalmu	White	Green	White	Oval	Half B
Con3	Taecheong	White	Green	White	Oval	Mostly A
Con4	Cheong-unmu	White	Green	White	Oval	Half B
Con5	Chorongmu	White	Green	White	Gourd	Mostly B
Con6	Mansa-hyeongtongmu	White	Green	White	Oval	Half B
Con7	Togwanggoldeumu	White	Green	White	Egg	Mostly B
Con8	Baeksinaltari	White	Green	White	Gourd	Mostly B
Con9	Syupeogiljomu	White	Green	White	Oval	Half B
Con10	Seohogoldeumu	White	Green	White	Oval	Half B

In root position in soil, Above: above soil line, Mostly A: mostly above soil line, Half B: half buried, Mostly B: mostly buried.

Appendix 2. Quantitative phenotype characters of 110 germplasms and 10 Korean cultivars

No.	IT No.	Total weight	Leaf weight	Root weight	Weight ratio (Top/Root)	Root length (cm)	Root width (cm)	Root ratio (Length/ Width)	Leaf length	Leaf width	Leaf ratio (Length/ Width)	Leaf number
1	32729	2140.0	451.7	1688.3	0.27	36.3	8.4	4.30	50.1	17.1	2.9	25.3
2	100590	2268.3	913.3	1355.0	0.67	24.1	9.8	2.50	56.9	17.0	3.4	35.7
3	100649	1921.7	546.7	1375.0	0.40	26.0	9.0	2.90	48.8	15.3	3.2	40.0
4	100678	2388.4	621.7	1766.7	0.35	26.0	10.3	2.50	53.8	17.8	3.0	32.0
5	100684	2381.7	816.7	1565.0	0.52	26.7	13.8	1.90	50.2	18.5	2.7	30.3
6	100689	1550.0	258.3	1291.7	0.20	21.0	10.4	2.00	35.3	14.3	2.5	18.3
7	100691	2360.0	550.0	1810.0	0.30	22.0	11.1	2.00	54.8	19.3	2.8	37.3
8	100695	2243.3	745.0	1498.3	0.50	24.8	10.2	2.40	47.7	15.3	3.1	42.0
9	102376	2203.3	801.7	1401.7	0.57	31.3	8.8	3.60	51.5	16.5	3.1	38.0
10	102378	2978.4	856.7	2121.7	0.40	41.0	9.2	4.50	50.3	16.7	3.0	43.3
11	102395	2268.3	988.3	1280.0	0.77	31.7	8.3	3.80	50.1	22.3	2.3	27.3
12	102560	1641.7	586.7	1055.0	0.56	21.7	9.1	2.40	46.8	19.6	2.4	14.0
13	103802	2288.3	768.3	1520.0	0.51	19.0	11.3	1.70	54.0	19.8	2.7	29.3
14	103811	2091.7	823.3	1268.3	0.65	19.8	10.7	1.90	55.0	20.2	2.7	27.0
15	104055	1324.3	301.0	1023.3	0.29	17.3	9.7	1.80	48.2	17.7	2.7	25.3
16	112253	1658.3	1013.3	645.0	1.57	28.2	6.3	4.50	46.3	15.3	3.0	47.3
17	112255	1686.7	706.7	980.0	0.72	36.3	6.6	5.50	46.8	13.5	3.5	47.0
18	112257	2996.6	1833.3	1163.3	1.58	40.7	7.2	5.70	57.8	23.3	2.5	47.0
19	112258	3308.3	390.0	2918.3	0.13	48.0	12.8	3.80	44.9	15.3	2.9	50.0
20	119000	1910.3	643.7	1266.7	0.51	22.5	10.1	2.20	50.0	12.2	4.1	28.7
21	136485	1681.7	951.7	730.0	1.30	28.7	6.2	4.60	49.5	17.8	2.8	41.3
22	136498	45.4	0.4	45.0	0.01	2.5	2.1	1.20	19.6	9.2	2.1	10.3
23	166993	2211.6	758.3	1453.3	0.52	35.7	8.1	4.40	53.2	19.7	2.7	27.3
24	166995	1801.6	273.3	1528.3	0.18	39.0	8.2	4.80	36.2	13.1	2.8	35.7
25	166997	2253.3	665.0	1588.3	0.42	36.7	8.4	4.40	47.2	19.0	2.5	40.7
26	185738	1186.6	328.3	858.3	0.38	19.7	9.5	2.10	41.3	18.7	2.2	16.3
27	188102	2045.0	515.0	1530.0	0.34	23.7	10.5	2.30	45.9	22.7	2.0	18.3
28	203316	1865.0	726.7	1138.3	0.64	9.3	13.5	0.70	45.3	19.3	2.4	18.0
29	203531	2161.7	836.7	1325.0	0.63	27.7	8.5	3.30	52.3	13.5	3.9	30.7
30	204160	1756.6	583.3	1173.3	0.50	20.7	9.5	2.20	49.2	17.3	2.8	23.0
31	208400	228.3	60.3	168.0	0.36	8.5	7.0	1.20	26.8	13.2	2.0	10.7
32	209937	1441.7	361.7	1080.0	0.33	13.0	12.3	1.10	44.5	15.3	2.9	12.3
33	209974	1420.0	220.0	1200.0	0.18	36.2	8.9	4.10	27.3	12.0	2.3	35.0
34	210203	2163.4	546.7	1616.7	0.34	39.7	8.0	5.00	39.3	15.5	2.5	37.7
35	213153	1838.4	546.7	1291.7	0.42	18.3	11.8	1.60	45.0	15.4	2.9	31.3
36	215011	2176.7	786.7	1390.0	0.57	19.8	10.8	1.80	49.0	16.8	2.9	24.7
37	215079	2455.0	938.3	1516.7	0.62	39.7	8.4	4.70	46.8	17.5	2.7	52.0
38	218925	1786.7	370.0	1416.7	0.26	22.8	9.8	2.30	47.5	14.2	3.4	20.0
39	220675	2018.3	473.3	1545.0	0.31	17.2	11.3	1.50	53.9	18.1	3.0	16.7
40	221952	991.7	271.7	720.0	0.38	17.8	7.6	2.30	40.1	11.6	3.5	16.3
41	221955	2836.7	761.7	2075.0	0.37	34.3	10.5	3.30	54.8	20.8	2.6	22.7

Appendix 2. Continued

No.	IT No.	Total weight	Leaf weight	Root weight	Weight ratio (Top/Root)	Root length (cm)	Root width (cm)	Root ratio (Length/ Width)	Leaf length	Leaf width	Leaf ratio (Length/ Width)	Leaf number
42	221956	2688.4	656.7	2031.7	0.32	32.7	41.8	0.80	54.3	19.2	2.8	18.3
43	221958	1490.0	186.7	1303.3	0.14	43.2	8.5	5.10	27	11.3	2.4	27.3
44	221959	2146.7	455.0	1691.7	0.27	31.0	9.0	3.40	42.8	13.8	3.1	25.0
45	223576	1293.3	253.3	1040.0	0.24	18.7	9.4	2.00	41.2	15.8	2.6	16.5
46	228857	1366.7	380.0	986.7	0.39	16.2	9.8	1.70	45.9	18.0	2.6	16.3
47	228870	1525.0	373.3	1151.7	0.32	13.5	11.6	1.20	48.3	17.3	2.8	15.3
48	250738	2383.3	843.3	1540.0	0.55	45.3	7.5	6.00	62.0	17.9	3.5	40.0
49	250765	2616.4	869.7	1746.7	0.50	45.4	7.3	6.20	46.5	17.8	2.6	40.3
50	250775	1475.0	411.7	1063.3	0.39	11.8	11.9	1.00	48.9	22.3	2.2	14.0
51	250777	1605.0	273.3	1331.7	0.21	16.2	12.4	1.30	46.2	18.3	2.5	12.7
52	250788	3073.3	788.3	2285.0	0.34	36.0	10.5	3.40	54.7	21.6	2.5	26.0
53	250790	2678.3	660.0	2018.3	0.33	32.3	10.6	3.00	49.8	16.4	3.0	19.0
54	250792	1481.7	340.0	1141.7	0.30	24.3	8.3	2.90	44.7	17.1	2.6	15.0
55	250794	1796.6	393.3	1403.3	0.28	25.0	9.1	2.70	44.9	19.9	2.3	17.0
56	261944	2176.6	698.3	1478.3	0.47	12.4	13.6	0.90	52.9	20.9	2.5	25.3
57	261947	2280.0	608.3	1671.7	0.36	33.5	9.1	3.70	51.7	18.7	2.8	19.7
58	261953	1295.0	341.7	953.3	0.36	12.7	12.0	1.10	42.3	14.5	2.9	28.0
59	261954	2276.7	1021.7	1255.0	0.81	32.4	6.9	4.70	53.5	21.8	2.5	40.7
60	261955	1645.0	418.3	1226.7	0.34	29.4	7.8	3.80	47.1	25.8	1.8	13.0
61	261967	2566.7	646.7	1920.0	0.34	32.8	9.5	3.50	58.6	18.1	3.2	16.7
62	261978	1888.3	700.0	1188.3	0.59	12.7	12.3	1.00	53.7	18.9	2.8	24.7
63	261989	2670.0	1031.7	1638.3	0.63	41.5	7.8	5.30	42.6	15.3	2.8	42.0
64	261995	1440.0	176.7	1263.3	0.14	39.1	8.1	4.80	26.2	10.3	2.5	26.7
65	262006	1988.3	688.3	1300.0	0.53	25.0	10.1	2.50	54.4	17.0	3.2	23.0
66	262018	1953.3	865.0	1088.3	0.79	25.8	8.5	3.00	51.3	16.5	3.1	31.3
67	262022	2750.0	608.3	2141.7	0.28	36.0	10.6	3.40	44.2	21.6	2.1	16.7
68	262023	1336.7	365.0	971.7	0.38	18.7	9.4	2.00	44.4	10.8	4.1	29.0
69	262031	743.3	270.0	473.3	0.57	10.0	9.8	1.00	46.6	15.5	3.0	22.7
70	262032	1571.6	243.3	1328.3	0.18	19.7	9.9	2.00	44.5	21.9	2.0	11.7
71	262036	1195.0	373.3	821.7	0.45	11.0	11.5	1.00	41.6	17.5	2.4	21.7
72	262037	2120.0	865.0	1255.0	0.69	33.8	7.5	4.50	48.6	15.8	3.1	44.0
73	262044	1560.0	405.0	1155.0	0.35	23.0	9.7	2.40	55.5	16.1	3.5	14.3
74	262049	1370.0	463.3	906.7	0.51	11.7	11.5	1.00	47.4	19.7	2.4	17.0
75	262050	1598.4	431.7	1166.7	0.37	10.8	12.9	0.80	47.5	18.1	2.6	19.0
76	262057	2025.0	758.3	1266.7	0.60	20.7	9.9	2.10	59.8	18.5	3.2	25.3
77	262070	1838.4	396.7	1441.7	0.28	10.2	13.6	0.80	52.6	21.2	2.5	17.3
78	262075	1720.0	416.7	1303.3	0.32	15.7	13.0	1.20	42.6	14.0	3.0	26.7
79	262076	1936.6	428.3	1508.3	0.28	13.1	14.1	0.90	44.3	13.8	3.2	28.3
80	264178	1596.6	493.3	1103.3	0.45	12.3	12.3	1.00	48.2	20.1	2.4	21.0

Appendix 2. Continued

No.	IT No.	Total weight	Leaf weight	Root weight	Weight ratio (Top/Root)	Root length (cm)	Root width (cm)	Root ratio (Length/ Width)	Leaf length	Leaf width	Leaf ratio (Length/ Width)	Leaf number
81	264180	2265.0	643.3	1621.7	0.40	12.7	15.0	0.80	50.2	13.2	3.8	30.7
82	276165	1768.3	300.0	1468.3	0.20	37.5	9.0	4.20	36.1	12.0	3.0	29.3
83	278269	1200.0	265.0	935.0	0.28	20.4	9.1	2.20	37.6	10.2	3.7	25.7
84	278682	1496.7	426.7	1070.0	0.40	12.8	10.8	1.20	44.3	15.9	2.8	20.3
85	278683	1235.0	226.7	1008.3	0.22	28.0	7.2	3.90	38.9	18.1	2.2	11.0
86	278684	1373.3	160.0	1213.3	0.13	38.2	8.2	4.70	27.1	10.4	2.6	24.3
87	278685	1621.7	326.7	1295.0	0.25	29.5	8.7	3.40	42.2	15.1	2.8	18.3
88	278727	155.0	30.0	125.0	0.24	6.8	6.4	1.10	21.1	9.3	2.3	11.0
89	283305	2213.3	903.3	1310.0	0.69	14.7	11.8	1.20	49.7	16.8	3.0	59.0
90	283312	1380.0	471.7	908.3	0.52	26.0	7.4	3.50	40.4	14.4	2.8	30.3
91	283317	1990.0	641.7	1348.3	0.48	13.7	13.4	1.00	40.2	18.7	2.2	22.7
92	289244	1271.7	461.7	810.0	0.57	10.7	10.7	1.00	46.5	16.7	2.8	20.0
93	291383	195.0	39.0	156.0	0.25	9.5	6.0	1.60	22.7	12.4	1.8	10.7
94	291423	3278.3	855.0	2423.3	0.35	21.5	14.5	1.50	52.6	17.6	3.0	40.3
95	291541	1645.0	541.7	1103.3	0.49	34.3	6.9	5.00	38.7	15.6	2.5	43.7
96	293006	1875.0	583.3	1291.7	0.45	11.0	13.3	0.80	40.4	14.9	2.7	48.0
97	293008	2195.0	616.7	1578.3	0.39	39.3	8.1	4.90	48.3	15.9	3.0	33.0
98	293028	2238.3	820.0	1418.3	0.58	16.2	11.8	1.40	50.3	18.0	2.8	30.3
99	293085	2271.7	901.7	1370.0	0.66	18.0	12.9	1.40	53.3	19.2	2.8	33.0
100	297120	1425.0	470.0	955.0	0.49	9.5	12.3	0.80	43.7	17.8	2.5	21.0
101	297172	68.3	13.0	55.3	0.24	5.5	4.7	1.20	14.2	8.4	1.7	8.7
102	297174	3420.0	583.3	2836.7	0.21	42.0	10.9	3.90	45.3	18.6	2.4	30.0
103	299326	1430.0	336.7	1093.3	0.31	33.0	7.1	4.60	61.5	19.2	3.2	13.0
104	299453	1226.7	261.7	965.0	0.27	32.2	6.3	5.10	40.2	18.6	2.2	12.3
105	305085	1513.0	668.0	845.0	0.79	15.8	8.5	1.90	57.7	18.9	3.1	32.3
106	305381	1693.4	441.7	1251.7	0.35	23.3	8.8	2.60	44.7	20.0	2.2	17.7
107	306869	1260.3	515.3	745.0	0.69	8.0	11.7	0.70	44.4	12.8	3.5	38.7
108	308359	1586.7	376.7	1210.0	0.31	11.7	12.4	0.90	43.7	16.8	2.6	19.0
109	308367	1208.4	286.7	921.7	0.31	23.7	7.7	3.10	39.8	16.0	2.5	18.0
110	308418	1383.4	166.7	1216.7	0.14	36.2	7.9	4.60	25.3	9.6	2.6	28.0
Con1	Gwailmu	1071.7	245.0	826.7	0.30	12.0	10.5	1.14	32.3	15.3	2.1	22.3
Con2	Meosjinmaskkalmu	2008.3	233.3	1775.0	0.13	21.2	11.4	1.86	35.6	14.1	2.5	29.7
Con3	Taecheong	2636.7	473.3	2163.3	0.22	24.2	11.8	2.05	41.5	17.3	2.4	28.3
Con4	Cheong-unmu	2380.0	340.0	2040.0	0.17	24.6	12.4	1.98	42.1	17.6	2.4	20.0
Con5	Chorongmu	2083.3	363.3	1720.0	0.21	19.2	12.0	1.60	45.6	16.4	2.8	26.7
Con6	Mansa-hyeongtongmu	2371.7	410.0	1961.7	0.21	24.2	11.7	2.07	36.2	11.8	3.1	33.0
Con7	Togwanggoldeumu	2113.3	165.0	1948.3	0.08	19.5	12.4	1.57	35.9	17.9	2.0	20.3
Con8	Baeksinaltari	723.3	135.0	588.3	0.23	12.3	11.7	1.05	38.1	12.3	3.1	19.0
Con9	Syupeogiljomu	2721.7	575.0	2146.7	0.27	23.2	12.0	1.93	48.3	18.9	2.5	27.7
Con10	Seohogoldeumu	2776.7	413.3	2363.3	0.17	25.8	12.6	2.05	43.1	17.3	2.5	23.7

Appendix 3. Glucosinolate contents and DPPH activity of 110 germplasms and 10 Korean cultivars

No.	IT No.	Glucoraphasatin (Average ± SD[z])	Glucoraphenin (Average ± SD[z])	Glucobrassicin (Average ± SD[z])	Glucoerucin (Average ± SD[z])	Glucoberteroin (Average ± SD[z])	Total glucosinolate (Average ± SD[z])	DPPH activity (%)
1	32729	11179.03 ± 925.59	2656.67 ± 263.93	124.37 ± 11.06	319.76 ± 34.11	24.41 ± 1.81	14304.24 ± 1234.00	22.29 ± 0.50
2	100590	10939.58 ± 1419.28	1778.49 ± 326.62	134.18 ± 19.91	360.22 ± 55.2	35.83 ± 1.74	13248.31 ± 1814.64	27.60 ± 1.46
3	100649	2793.50 ± 266.26	546.68 ± 66.83	28.93 ± 3.83	27.23 ± 2.01	4.36 ± 0.69	3400.70 ± 338.45	26.02 ± 0.90
4	100678	984.87 ± 121.39	472.46 ± 58.10	8.27 ± 1.37	9.50 ± 1.06	0.66 ± 0.32	1475.75 ± 181.93	19.08 ± 1.52
5	100684	5945.12 ± 390.38	1713.83 ± 149.23	220.70 ± 19.95	133.37 ± 13.98	7.90 ± 0.49	8020.92 ± 571.75	30.90 ± 1.76
6	100689	975.52 ± 126.22	747.44 ± 91.26	9.40 ± 1.31	13.62 ± 1.78	1.40 ± 0.52	1747.39 ± 220.09	31.48 ± 0.68
7	100691	6291.06 ± 689.13	1917.39 ± 198.31	39.06 ± 5.74	102.17 ± 11.39	7.99 ± 1.19	8357.66 ± 900.7	31.26 ± 0.79
8	100695	8476.9 ± 735.11	2411.44 ± 167.18	288.21 ± 37.26	349.47 ± 23.76	34.62 ± 2.69	11560.65 ± 964.07	20.80 ± 0.49
9	102376	11261.78 ± 1145.72	1502.84 ± 220.68	76.77 ± 8.16	324.42 ± 40.68	14.46 ± 1.53	13180.27 ± 1411.31	15.70 ± 1.29
10	102378	11695.28 ± 1055.43	2455.14 ± 398.31	312.01 ± 23.76	291.55 ± 36.15	20.95 ± 1.55	14774.93 ± 1514.06	14.70 ± 2.24
11	102395	5475.85 ± 383.85	1328.9 ± 162.74	96.22 ± 12.31	124.27 ± 7.75	7.59 ± 1.52	7032.84 ± 564.16	21.60 ± 0.21
12	102560	9565.98 ± 355.89	2899.40 ± 124.44	184.77 ± 5.41	378.23 ± 9.46	15.62 ± 0.28	13043.99 ± 492.01	16.02 ± 2.06
13	103802	2815.52 ± 219.04	920.06 ± 104.04	94.09 ± 10.92	36.37 ± 2.68	4.59 ± 0.54	3870.64 ± 336.22	19.18 ± 0.42
14	103811	210.71 ± 18.73	57.83 ± 9.42	0.87 ± 0.24	4.72 ± 0.09	0.24 ± 0.15	274.37 ± 23.51	10.43 ± 2.22
15	104055	2462.68 ± 284.12	1045.55 ± 115.08	55.75 ± 7.52	36.83 ± 4.43	3.47 ± 0.86	3604.28 ± 411.71	18.29 ± 2.17
16	112253	252.61 ± 26.96	43.70 ± 5.47	3.93 ± 0.31	3.70 ± 0.65	0.18 ± 0.09	304.12 ± 32.98	12.47 ± 0.98
17	112255	7013.84 ± 811.76	1871.35 ± 326.49	122.35 ± 12.8	98.84 ± 13.09	11.33 ± 0.69	9117.71 ± 1161.6	16.09 ± 2.80
18	112257	9441.1 ± 750.17	936.32 ± 120.22	82.20 ± 6.39	215.41 ± 21.63	11.19 ± 0.72	10686.21 ± 897.43	19.89 ± 2.80
19	112258	8996.09 ± 747.33	1596.7 ± 212.78	33.80 ± 2.64	445.24 ± 43.83	20.56 ± 1.20	11092.39 ± 1006.74	18.59 ± 2.03
20	119000	9305.38 ± 986.46	2231.75 ± 405.44	60.17 ± 8.26	284.83 ± 45.92	19.36 ± 3.54	11901.48 ± 1449.54	16.47 ± 1.35
21	136485	8551.15 ± 740.75	735.01 ± 75.20	43.17 ± 5.30	247.89 ± 23.55	23.8 ± 1.33	9601.02 ± 830.78	32.49 ± 2.57
22	136498	3116.76 ± 306.78	901.86 ± 105.92	29.20 ± 2.68	48.98 ± 5.56	2.89 ± 0.17	4099.69 ± 417.29	52.69 ± 0.59
23	166993	508.27 ± 41.06	379.03 ± 34.81	4.71 ± 0.18	6.54 ± 0.97	0.38 ± 0.25	898.94 ± 77.13	18.29 ± 0.20
24	166995	5828.08 ± 876.35	1862.04 ± 430.71	225.72 ± 32.85	191.62 ± 39.33	4.67 ± 0.37	8112.13 ± 1377.45	28.77 ± 1.54
25	166997	423.77 ± 49.42	207.6 ± 27.75	2.08 ± 0.33	6.37 ± 0.39	0.29 ± 0.26	640.11 ± 77.01	21.26 ± 0.30
26	185738	691.98 ± 50.89	316.58 ± 44.00	8.12 ± 0.19	16.64 ± 2.18	0.49 ± 0.29	1033.8 ± 96.62	18.72 ± 1.10

Appendix 3. Continued

No.	IT No.	Glucoraphasatin (Average ± SD[z])	Glucoraphenin (Average ± SD[z])	Glucobrassicin (Average ± SD[z])	Glucoerucin (Average ± SD[z])	Glucoberteroin (Average ± SD[z])	Total glucosinolate (Average ± SD[z])	DPPH activity (%)
27	188102	1615.38 ± 212.87	924.99 ± 132.93	18.92 ± 2.07	23.6 ± 4.24	2.21 ± 0.28	2585.11 ± 349.14	16.35 ± 1.66
28	203316	3715.43 ± 452.50	1964.29 ± 284.38	158.21 ± 17.09	74 ± 12.10	9.11 ± 1.91	5921.04 ± 766.50	20.27 ± 1.55
29	203531	3095.72 ± 309.97	960.01 ± 100.11	6.43 ± 0.65	51.49 ± 7.02	4.38 ± 0.48	4118.03 ± 418.05	16.3 ± 1.14
30	204160	4668.71 ± 590.22	1118.75 ± 181.58	59.03 ± 8.37	98.51 ± 14.91	9.54 ± 1.09	5954.54 ± 795	32.84 ± 0.63
31	208400	814.68 ± 102.08	499.81 ± 132.81	5.28 ± 0.80	13.73 ± 1.72	0.49 ± 0.52	1334 ± 237.12	59.81 ± 0.69
32	209937	3424.68 ± 322.98	1808.17 ± 184.18	88.7 ± 8.17	62.04 ± 7.73	8.31 ± 1.33	5391.9 ± 520.24	23.78 ± 0.64
33	209974	5093.86 ± 688.86	1111.8 ± 163.98	90.38 ± 12.64	172.77 ± 33.28	5.36 ± 0.62	6474.17 ± 890.91	27.58 ± 1.73
34	210203	4050.15 ± 447.00	814.92 ± 85.05	8.69 ± 1.15	89.41 ± 9.81	13.08 ± 1.31	4976.25 ± 537.67	24.90 ± 0.34
35	213153	662.76 ± 62.28	510.75 ± 42.22	1.56 ± 0.04	12.63 ± 1.68	0.41 ± 0.11	1188.11 ± 105.84	18.81 ± 0.51
36	215011	12921.97 ± 1252.18	2527.07 ± 295.34	134.99 ± 15.18	440.03 ± 37.63	49.69 ± 5.37	16073.75 ± 1549.92	28.79 ± 2.41
37	215079	9803.19 ± 806.83	1700.19 ± 165.18	26.87 ± 1.41	348.51 ± 36.71	19.78 ± 1.74	11898.55 ± 1004.35	12.85 ± 1.84
38	218925	11321.86 ± 1208.50	2160.83 ± 292.20	165.04 ± 11.76	512.00 ± 66.73	18.62 ± 3.07	14178.35 ± 1579.41	26.19 ± 0.88
39	220675	7562.46 ± 1027.86	3389.28 ± 570.44	296.17 ± 45.93	199.11 ± 36.77	23.76 ± 2.53	11470.77 ± 1667.16	19.78 ± 1.69
40	221952	8634.13 ± 975.11	3140.49 ± 364.04	338.87 ± 36.89	305.60 ± 30.6	43.56 ± 3.06	12462.65 ± 1402.28	30.83 ± 2.51
41	221955	7544.73 ± 930.51	3883.83 ± 522.85	28.75 ± 6.21	249.00 ± 28.87	16.74 ± 1.17	11723.95 ± 1461.62	33.26 ± 1.74
42	221956	7179.87 ± 775.79	2988.78 ± 407.06	84.45 ± 5.87	227.86 ± 31.48	17.77 ± 0.82	10498.74 ± 1200.09	21.33 ± 1.51
43	221958	325.33 ± 36.35	174.68 ± 19.07	5.33 ± 0.55	6.82 ± 1.01	0.15 ± 0.16	512.31 ± 56.99	18.79 ± 0.36
44	221959	1407.71 ± 166.67	616.06 ± 115.42	23.68 ± 2.93	27.61 ± 2.34	1.21 ± 0.43	2076.27 ± 259.33	34.57 ± 0.56
45	223576	9678.29 ± 1323.37	4284.93 ± 551.12	224.54 ± 25.15	319.74 ± 63.01	27.68 ± 6.77	14535.19 ± 1926.59	19.13 ± 1.24
46	228857	8046.57 ± 861.63	3748.14 ± 391.37	203.22 ± 31.25	291.04 ± 31.17	29.59 ± 3.50	12318.56 ± 1309.22	30.39 ± 1.30
47	228870	11638.83 ± 1215.04	5105.15 ± 531.94	631.39 ± 129.13	371.71 ± 66.63	42.26 ± 5.75	17789.35 ± 1943.58	15.50 ± 1.49
48	250738	10414.1 ± 1215.68	1451.88 ± 179.06	113.52 ± 13.35	319.07 ± 56.43	23.71 ± 3.37	12322.28 ± 1465.38	20.90 ± 2.22
49	250765	5443.16 ± 507.96	1471.51 ± 169.37	33.07 ± 3.07	158.79 ± 22.78	6.64 ± 0.84	7113.17 ± 702.02	17.24 ± 2.05
50	250775	6514.06 ± 588.64	2636.95 ± 282.67	76.41 ± 13.88	187.94 ± 17.38	20.89 ± 1.41	9436.24 ± 902.71	24.64 ± 1.09
51	250777	1161.23 ± 62.82	791.86 ± 133.05	35.20 ± 0.57	20.95 ± 0.95	1.62 ± 0.13	2010.85 ± 190.33	17.84 ± 2.31
52	250788	5719.88 ± 455.08	3293.35 ± 115.39	99.63 ± 6.72	174.70 ± 22.87	9.98 ± 0.35	9297.54 ± 599.10	23.80 ± 0.88

Appendix 3. Continued

No.	IT No.	Glucoraphasatin (Average ± SD[z])	Glucoraphenin (Average ± SD[z])	Glucobrassicin (Average ± SD[z])	Glucoerucin (Average ± SD[z])	Glucoberteroin (Average ± SD[z])	Total glucosinolate (Average ± SD[z])	DPPH activity (%)
53	250790	7527.83 ± 836.51	4421.21 ± 418.65	129.48 ± 12.02	192.34 ± 35.84	13.09 ± 2.04	12283.96 ± 1257.89	40.63 ± 12.15
54	250792	6315.22 ± 618.27	1035.81 ± 107.50	246.75 ± 21.10	138.07 ± 20.15	13.6 ± 0.83	7749.45 ± 759.18	16.00 ± 3.17
55	250794	7707.88 ± 564.45	2828.78 ± 381.80	186.71 ± 24.00	214.64 ± 23.35	23.55 ± 1.12	10961.55 ± 982.87	22.08 ± 2.48
56	261944	4715.3 ± 607.44	496.67 ± 64.25	119.13 ± 15.15	100.22 ± 11.55	5.38 ± 0.39	5436.7 ± 697.13	28.00 ± 0.97
57	261947	8035.35 ± 729.44	3329.76 ± 180.91	70.63 ± 8.33	263.42 ± 41.36	13.94 ± 3.22	11713.1 ± 937.09	27.53 ± 3.00
58	261953	4415.55 ± 456.00	1237.84 ± 144.58	73.36 ± 9.98	79.53 ± 7.91	7.44 ± 0.99	5813.72 ± 613.45	32.54 ± 1.56
59	261954	6710.18 ± 713.28	2105.59 ± 250.08	64.73 ± 12.06	126.48 ± 13.04	6.60 ± 0.21	9013.58 ± 987.87	14.61 ± 1.67
60	261955	7185.08 ± 813.15	1960.97 ± 255.23	196.25 ± 28.85	187.04 ± 18.21	17.68 ± 1.06	9547.02 ± 1115.79	21.06 ± 0.80
61	261967	8442.83 ± 1006.26	3438.58 ± 446.30	124.64 ± 18.12	262.36 ± 25.49	23.77 ± 1.89	12292.18 ± 1482.31	21.88 ± 1.94
62	261978	974.68 ± 48.05	302.64 ± 22.48	7.83 ± 0.38	13.93 ± 0.93	0.79 ± 0.32	1299.86 ± 68.28	24.38 ± 3.71
63	261989	10760.66 ± 977.97	3121.63 ± 339.26	26.72 ± 2.51	520.92 ± 77.72	32.17 ± 1.59	14462.1 ± 1329.74	20.40 ± 2.37
64	261995	2167.39 ± 226.85	1547.31 ± 160.31	2.98 ± 0.19	40.01 ± 5.13	2.80 ± 0.31	3760.5 ± 370.32	18.38 ± 3.10
65	262006	423.06 ± 22.30	248.22 ± 15.75	4.21 ± 0.13	7.90 ± 0.20	0.26 ± 0.09	683.65 ± 30.19	21.39 ± 1.64
66	262018	147.42 ± 6.48	29.23 ± 1.59	0.65 ± 0.07	2.58 ± 0.18	0.05 ± 0.06	179.92 ± 7.33	24.59 ± 2.02
67	262022	8475.89 ± 920.77	4146.82 ± 408.09	38.22 ± 2.66	310.78 ± 43.94	28.01 ± 2.13	12999.72 ± 1372.38	24.59 ± 2.17
68	262023	184.02 ± 22.47	59.04 ± 8.60	1.36 ± 0.13	2.40 ± 0.09	0.00 ± 0.00	246.82 ± 31.22	27.57 ± 2.23
69	262031	1082.49 ± 98.07	778.41 ± 50.81	10.68 ± 0.77	32.74 ± 3.86	3.51 ± 1.01	1907.83 ± 151.27	27.64 ± 3.18
70	262032	772.05 ± 74.89	730.38 ± 35.82	13.27 ± 1.10	15.66 ± 1.79	1.40 ± 0.48	1532.76 ± 103.77	17.43 ± 1.98
71	262036	7756.15 ± 736.74	3407.97 ± 228.30	533.12 ± 50.83	150.55 ± 24.20	11.75 ± 1.03	11859.54 ± 1018.87	45.69 ± 3.02
72	262037	7161.74 ± 776.01	2300.09 ± 265.61	12.54 ± 1.41	202.79 ± 35.52	15.63 ± 1.85	9692.79 ± 1066.16	15.66 ± 0.80
73	262044	694.95 ± 64.48	313.93 ± 21.21	16.01 ± 1.00	9.62 ± 0.98	0.20 ± 0.11	1034.71 ± 83.71	19.63 ± 1.93
74	262049	1747.75 ± 161.08	749.16 ± 100.01	143.81 ± 16.09	17.98 ± 1.41	2.16 ± 0.72	2660.86 ± 279.13	38.75 ± 1.29
75	262050	2529.17 ± 263.58	973.73 ± 124.64	50.72 ± 6.24	51.29 ± 5.31	5.07 ± 0.52	3609.98 ± 399.91	31.08 ± 1.87
76	262057	1587.23 ± 144.12	628.61 ± 72.63	14.36 ± 1.54	24.32 ± 2.05	1.89 ± 0.39	2256.41 ± 220.03	19.37 ± 1.95
77	262070	2899.72 ± 228.78	1012.70 ± 48.97	106.6 ± 5.25	41.77 ± 3.90	3.43 ± 0.60	4064.22 ± 278.41	18.43 ± 5.71
78	262075	4921.87 ± 389.66	2323.96 ± 179.26	22.73 ± 1.28	118.28 ± 11.36	9.53 ± 0.73	7396.36 ± 555.24	23.91 ± 2.95

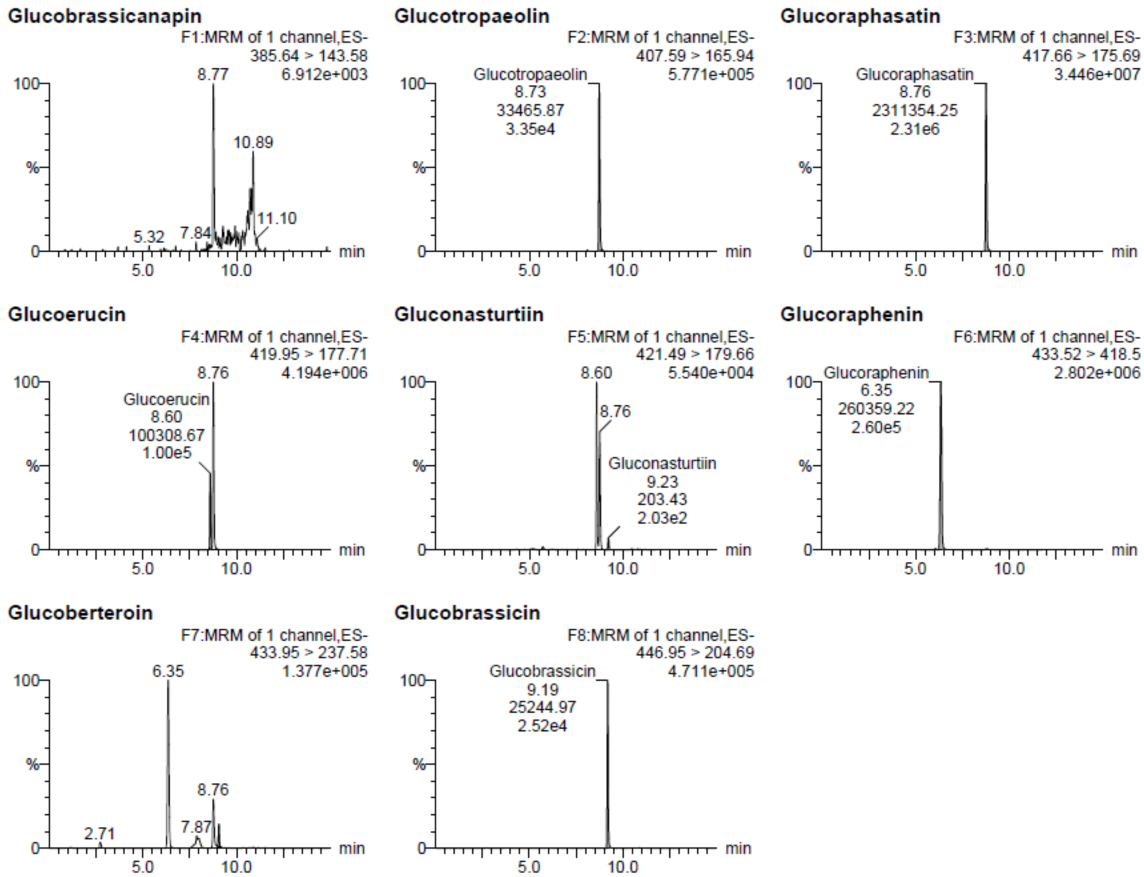
Appendix 3. Continued

No.	IT No.	Glucoraphasatin (Average ± SD^z)	Glucoraphenin (Average ± SD^z)	Glucobrassicin (Average ± SD^z)	Glucoerucin (Average ± SD^z)	Glucoberteroin (Average ± SD^z)	Total glucosinolate (Average ± SD^z)	DPPH activity (%)
79	262076	8207.53 ± 662.86	3318.56 ± 198.15	74.34 ± 4.57	276.04 ± 36.80	19.23 ± 0.95	11895.69 ± 743.41	27.9 ± 3.08
80	264178	3420.25 ± 99.52	1329.92 ± 135.41	148.07 ± 11.80	58.97 ± 1.80	6.10 ± 0.37	4963.3 ± 220.64	63.05 ± 33.28
81	264180	4447.28 ± 431.07	1930.04 ± 240.28	57.13 ± 5.99	95.24 ± 7.94	11.49 ± 0.78	6541.17 ± 684.68	28.09 ± 1.21
82	276165	609.89 ± 54.54	400.04 ± 36.88	10.52 ± 0.49	9.58 ± 0.86	0.41 ± 0.27	1030.44 ± 88.46	20.02 ± 4.00
83	278269	3356.76 ± 326.57	1093.71 ± 163.91	40.52 ± 3.92	48.08 ± 4.83	2.19 ± 0.28	4541.26 ± 494.96	18.96 ± 1.68
84	278682	4711.53 ± 382.95	1110.76 ± 171.65	591.27 ± 42.72	64.53 ± 6.23	4.90 ± 0.99	6482.99 ± 543.26	55.17 ± 4.43
85	278683	11663.38 ± 1257.80	2894.93 ± 358.63	703.41 ± 76.07	454.01 ± 80.97	40.22 ± 1.09	15755.96 ± 1713.63	16.07 ± 2.60
86	278684	8767.59 ± 1025.95	2648.30 ± 217.99	72.76 ± 8.83	347.88 ± 63.10	18.52 ± 2.29	11855.05 ± 1309.80	12.68 ± 16.25
87	278685	1316.78 ± 102.33	1104.85 ± 72.23	5.29 ± 0.38	21.07 ± 2.20	0.58 ± 0.25	2448.57 ± 133.23	4.26 ± 25.19
88	278727	1266.86 ± 129.63	792.83 ± 41.70	18.25 ± 1.19	18.19 ± 1.93	1.31 ± 0.06	2097.44 ± 143.08	46.29 ± 0.53
89	283305	12816.85 ± 1468.17	2342.25 ± 298.43	96.38 ± 9.67	466.24 ± 47.87	31.53 ± 2.14	15753.25 ± 1825.81	31.67 ± 1.56
90	283312	4895.8 ± 372.14	1234.99 ± 26.07	27.01 ± 2.09	97.90 ± 12.57	4.57 ± 0.37	6260.26 ± 389.30	17.95 ± 2.52
91	283317	5192.73 ± 526.49	1330.03 ± 147.24	96.69 ± 9.80	102.34 ± 16.28	9.82 ± 0.96	6731.6 ± 678.03	14.21 ± 1.99
92	289244	5002.57 ± 662.49	1517.41 ± 255.09	324.15 ± 50.58	82.35 ± 10.63	5.89 ± 1.64	6932.37 ± 979.65	44.99 ± 1.48
93	291383	1523.63 ± 196.73	445.56 ± 63.93	14.41 ± 1.47	28.15 ± 2.76	2.65 ± 0.25	2014.41 ± 263.61	36.14 ± 0.46
94	291423	9723.58 ± 1019.92	1730.22 ± 246.64	334.58 ± 42.10	466.17 ± 36.92	30.45 ± 2.61	12285.01 ± 1346.28	14.88 ± 0.14
95	291541	1913.56 ± 76.47	976.86 ± 113.15	8.10 ± 0.22	39.47 ± 1.05	2.20 ± 0.19	2940.19 ± 187.07	21.94 ± 1.73
96	293006	7856.62 ± 573.90	1144.05 ± 52.40	28.61 ± 2.51	251.52 ± 26.31	13.26 ± 0.79	9294.06 ± 625.16	17.01 ± 2.99
97	293008	6179.58 ± 630.56	1514.71 ± 91.55	14.66 ± 1.52	161.65 ± 23.71	12.20 ± 2.30	7882.8 ± 745.08	22.57 ± 1.86
98	293028	8425.24 ± 679.54	934.71 ± 75.56	32.62 ± 2.15	249.98 ± 31.27	13.41 ± 1.70	9655.96 ± 747.74	20.73 ± 2.25
99	293085	7402.03 ± 706.58	2230.55 ± 229.32	93.13 ± 23.58	237.61 ± 22.52	14.25 ± 1.36	9977.56 ± 976.05	24.63 ± 0.41
100	297120	6933.66 ± 428.54	2029.14 ± 106.05	449.10 ± 30.50	170.32 ± 16.06	12.56 ± 0.18	9594.78 ± 504.88	46.39 ± 0.74
101	297172	469.18 ± 44.07	163.82 ± 11.35	2.03 ± 0.14	6.77 ± 0.70	0.19 ± 0.07	641.98 ± 52.73	30.53 ± 3.13
102	297174	9182.81 ± 914.73	2213.60 ± 213.38	203.22 ± 20.46	320.68 ± 22.55	20.87 ± 1.01	11941.19 ± 1162.16	18.98 ± 0.05
103	299326	9389.02 ± 492.80	3128.66 ± 149.46	380.53 ± 24.92	363.06 ± 34.87	43.72 ± 4.16	13305 ± 612.02	29.43 ± 3.52
104	299453	12495.36 ± 805.01	4946.47 ± 302.76	403.09 ± 17.58	534.53 ± 51.15	59.07 ± 3.24	18438.52 ± 970.31	17.77 ± 3.55

Appendix 3. Continued

No.	IT No.	Glucoraphasatin (Average ± SD[z])	Glucoraphenin (Average ± SD[z])	Glucobrassicin (Average ± SD[z])	Glucoerucin (Average ± SD[z])	Glucoberteroin (Average ± SD[z])	Total glucosinolate (Average ± SD[z])	DPPH activity (%)
105	305085	6097.55 ± 425.32	2012.43 ± 326.01	255.72 ± 33.40	154.40 ± 12.75	11.19 ± 0.80	8531.3 ± 792.97	21.49 ± 0.56
106	305381	5909.04 ± 581.05	1970.40 ± 280.71	372.52 ± 52.71	212.09 ± 26.37	20.16 ± 4.22	8484.21 ± 941.19	28.34 ± 0.29
107	306869	10571.92 ± 1141.35	5653.20 ± 731.55	1243.88 ± 187.47	514.58 ± 49.20	34.30 ± 2.97	18017.88 ± 2108.07	29.77 ± 0.94
108	308359	7635.26 ± 195.76	3196.07 ± 309.54	166.23 ± 3.77	218.03 ± 9.36	16.94 ± 0.74	11232.53 ± 421.18	21.61 ± 2.78
109	308367	5906.01 ± 157.17	1353.42 ± 168.61	250.59 ± 11.37	198.84 ± 7.28	27.66 ± 2.92	7736.50 ± 246.11	22.85 ± 1.54
110	308418	123.76 ± 16.36	26.28 ± 3.50	1.27 ± 0.11	2.97 ± 0.20	0.02 ± 0.02	154.30 ± 20.09	29.52 ± 0.16
Con1	Gwailmu	2531.25 ± 296.06	1247.67 ± 191.43	268.36 ± 44.46	40.86 ± 4.88	5.31 ± 1.24	4093.45 ± 536.93	43.31 ± 0.54
Con2	Meosjinmaskkalmu	4702 ± 522.40	694.89 ± 101.45	30.79 ± 4.29	112.71 ± 11.91	4.72 ± 1.30	5545.11 ± 641.26	26.91 ± 1.04
Con3	Taecheong	6437.09 ± 545.29	509.63 ± 51.17	7.94 ± 1.22	120.97 ± 16.81	5.05 ± 0.93	7080.67 ± 610.67	23.36 ± 1.83
Con4	Cheong-unmu	6210.01 ± 775.16	898.02 ± 122.53	27.43 ± 4.23	146.01 ± 17.69	10.01 ± 1.78	7291.48 ± 920.80	21.66 ± 2.47
Con5	Chorongmu	6781.61 ± 611.26	532.23 ± 62.75	25.82 ± 3.70	123.83 ± 8.55	8.89 ± 0.35	7472.38 ± 685.75	30.67 ± 0.49
Con6	Mansa-hyeongtongmu	7019.84 ± 922.97	984.58 ± 148.58	44.71 ± 7.02	189.20 ± 26.21	12.25 ± 1.57	8250.57 ± 1105.98	26.58 ± 0.92
Con7	Togwanggoldeumu	7968.49 ± 453.95	991.70 ± 64.54	37.75 ± 2.59	169.24 ± 16.43	8.83 ± 0.85	9176.01 ± 492.2	21.92 ± 3.48
Con8	Baeksinaltari	7989.39 ± 755.68	1144.97 ± 126.38	185.86 ± 32.79	146.49 ± 14.07	10.29 ± 1.77	9477.00 ± 929.50	26.91 ± 0.43
Con9	Syupeogiljomu	9053.54 ± 738.81	1307.13 ± 136.26	48.53 ± 6.08	212.05 ± 17.12	15.36 ± 1.48	10636.61 ± 894.57	24.51 ± 0.20
Con10	Seohogoldeumu	9247.03 ± 706.53	1256.86 ± 111.22	59.03 ± 8.46	292.94 ± 21.42	17.25 ± 1.53	10873.12 ± 843.35	29.27 ± 0.44

[z]SD means standard deviation.



Appendix 4. MS information of eight glucosinolate standards.