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Profiles of major glucosinolates in different parts of white cabbage and their evolutions during processing into vegetable powder by various methods

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Abstract

Commercially discarded portions, i.e., outer leaves and core, as well as edible leaves, of white cabbage (*Brassica oleracea* L. var. *capitata*) were processed into vegetable powder rich in glucosinolates (GLSs). Four GLSs, i.e., sinigrin, glucoraphanin, glucoerucin, and glucobrassicin, were quantified in both fresh and processed samples. Fresh outer leaves and core contained higher GLSs contents comparable to edible leaves. Steam blanching, microwave-assisted blanching and ultrasound-assisted blanching were tested prior to hot air drying at 80°C to inhibit polyphenol oxidase, peroxidase, and myrosinase, which is the endogenous enzyme responsible for the degradation of GLSs during processing. Steam blanching for 3 min was eventually selected as it required the shortest time and had minute effect on GLSs. Drying caused significant reduction in GLSs contents. Glucobrassicin was noted to be the most heat-sensitive, while glucoraphanin was the most heat-stable. GLSs content in vegetable powder was approximately 82 - 84% of those in the fresh samples.

Introduction

Epidemiological studies have shown that adequate consumption of *Brassica* vegetables is associated with reduced risk of certain cancers such as lung, colorectal, breast, and prostate cancers (Higdon *et al*., 2007). Glucosinolates (GLSs) have been identified as naturally occurring substances responsible for the anticarcinogenic properties of Brassica vegetables. Such substances are a group of sulphur-containing plant secondary metabolites, which can be further hydrolysed by the enzyme myrosinase (MYS) to form different products, e.g., thiocyanates, isothiocyanates, epithionitrile, nitrile, and oxazoidine-thione (Wennberg *et al*., 2006). In fact, these derivative products (especially isothiocyanates) that possess anticarcinogenic activities. GLSs are naturally stable compounds that are located in plant S-cells, while MYS are stored separately in the so-called myrosin cells (Lee *et al*., 2017). The conversion of GLSs into the hydrolysed products occurs when plant cells are ruptured during processing steps such as slicing and chopping (Jones *et al*., 2006). The hydrolysis of GLSs can also occur in human body via colonic microflora activity (Krul *et al*., 2002). Therefore, the consumption of vegetables with high contents of GLSs could be beneficial.

The types and contents of GLSs vary widely among different vegetables as well as among cultivars, genotypes, harvest seasons, and even plant parts (Charron *et al*., 2005; Wiesner *et al*., 2013). The reduction of different GLSs during processing of Brassica vegetables has been widely reported (Ciska and Kozłowska, 2001). Wennberg *et al*. (2006), for example, studied the effect of hot-water blanching on GLSs contents of white cabbage (*Brassica oleracea* L. var. *capitata*). The total GLSs content decreased by 50 - 74% due to both enzymatic and thermal degradation of the compounds; leaching of the compounds into blanched water was also noted as another reason for the decreased content. Tanongkankit *et al*. (2010) later studied the effects of vegetable preparation and blanching methods in combination with hot air drying at 80°C on the retention of cabbage

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antioxidants. Steam blanching the whole cabbage leaves and then slicing prior to hot air drying at 80°C were recommended as the combined processing steps that should be used to prepare the vegetable powder with the highest antioxidant activity. The information on different key GLSs in various parts of cabbage is unfortunately not available thus far. This information is of importance as it would allow better selection of the vegetable part for further use.

Several advanced technologies can be used to augment the conventional processing technologies, including blanching. Microwave can, for example, be applied for such a purpose. Effective inactivation of deleterious enzymes, e.g., polyphenol oxidase (PPO), and even endogenous enzymes, e.g., MYS, via the use of microwave has been reported (de Ancos *et al*., 1999; Rungapamestry *et al*., 2006; Chávez-Reyes *et al*., 2013). The inactivation of MYS is in many cases preferred since it would inhibit the hydrolysis of GLSs. As mentioned earlier, a vegetable product with higher GLSs content can be a desirable choice. Ultrasound can also be used to assist blanching. The application of ultrasound has been shown to significantly enhance the rates of inactivation of various degradative enzymes, including pectin methylesterase (PME), polygalacturonase (PG), lipoxygenase (LOX), peroxidase (POD), and PPO even at a milder temperature (Dang *et al*., 2012; Terefe *et al*., 2015; Mujeeda Banu *et al*., 2016). Presently, the effects of these processing methods on the profiles of GLSs in different parts of white cabbage are also not available.

The present work thus aimed at studying the profiles of important GLSs, i.e., sinigrin, glucoraphanin, glucoerucin, and glucobrassicin, in different parts of white cabbage (i.e., outer leaves, edible leaves, and core). Selected blanching methods, i.e., steam blanching (SB), microwave-assisted blanching (MAB), and ultrasound-assisted blanching (UAB) were investigated as the means to inactivate deleterious enzymes in fresh cabbages. The selected blanching method and condition must also be sufficient to inhibit MYS to alleviate further degradation of GLSs during subsequent drying. The GLSs contents in vegetable powder produced from three parts of cabbage were also determined to demonstrate the potential use of the powder as a functional food ingredient.

Materials and methods

Sample preparation

White cabbage was obtained from a specific seller at Pak Klong wholesale market in Bangkok, Thailand. The mass of each cabbage head was in the range of 0.8 - 1.2 kg. The vegetable was refrigerated at 4°C until further analyses, which did not exceed three days

Prior to each experiment, the cabbage heads were washed under running tap water; the leaves on the outermost layer of each head were then removed. The leaves on the second and third layers, which are in dark green colour and usually discarded during vegetable preparation at the market, were taken and labelled as the "outer leaves" sample. The core of the cabbage heads were removed using a cork borer, and labelled as the "core" sample. The inner leaves on the middle layers between the outer leaves and the core with nearly white colour were taken and labelled as the "edible leaves" sample.

Determination of suitable blanching conditions

Whole outer leaves and whole edible leaves as well as core with the diameter in the range of 25 mm and thickness of 3 mm were subjected to different blanching methods and conditions.

SB was performed using a water bath (Heto, AT 110, Allerod, Denmark); each sample was placed as a single layer on a perforated tray suspended over boiling water (~ 98°C).

MAB was performed in a domestic microwave oven (Samsung, GE-872D, Port Klang, Malaysia) at input powers of 300, 450, and 600 W. In the case of MAB, our preliminary results showed that MAB of a sample without addition of water resulted in significantly uneven heating; burnt spots on the samples were clearly observed. However, when water was added, heating was more uniform as water could flow around and transport heat more uniformly to different parts of the samples under heating. Therefore, MAB experiments were eventually performed by placing a whole outer or edible leave of cabbage or ~30 g of the core in a glass bowl containing 500 mL of distilled water during heating. The specific absorbed microwave powers in the cases of MAB at 300, 450, and 600 W were 0.50-1.16, 0.79 - 1.83 and 1.06 - 2.88 W/g, respectively.

UAB was performed using an ultrasonic bath (Elma, Elmasonic P, Singen, Germany). A whole outer or edible leave of cabbage or ~30 g of the core was placed in the ultrasonic bath containing 1 L of distilled water and sonicated at a frequency of 37 kHz, a set power of 320 W and at 80°C (or absorbed ultrasonic power of 0.55 - 1.54 W/g). The temperature evolution of a cabbage sample during SB and UAB were measured using a type-T thermocouple, which was inserted into the centre of the sample and connected to a data logger (Yokogawa, DX112,

Tokyo, Japan). A fibre-optic thermometer (Luxtron, m600, Santa Clara, CA) was used to monitor the sample temperature during MAB.

A suitable blanching condition for each part of the cabbage was determined based on PPO, POD, and MYS inactivation. Following blanching, the sample was immediately cooled in cold water (4°C). The samples was chopped using an electric chopper (Tefal, DPA130, Ecully, France) for 1 min to obtain the sample with the size of approximately 1 - 3 mm.

Preparation of vegetable powder

Drying was performed by spreading around 200 g of each prepared sample as a single layer over a cooking sheet placed on a tray. The sample was dried at 80°C in a laboratory-scale hot air oven (Memmert, UF110, Schwabach, Germany). Next, 3 - 5 g of the sample was taken out at various intervals to determine its moisture content. Drying was conducted until a constant mass was achieved; the moisture content at such a point was then referred to as the equilibrium moisture content. Once a complete drying curve was constructed, the curve was used to determine the time required to dry the sample to the desired final moisture content of around 10% dry mass (Larrauri, 1999). The moisture content of each sample was determined using AOAC method no. 987.25 (AOAC, 2000). Following drying, the dried sample was ground into fine powder using a cyclone mill (Tecator, 1093, Höganäs, Sweden) and sieved using a sieve analyser (Retsch, AS200 Basic, Haan, Germany) to obtain a particle size of less than 450 μm (Larrauri, 1999).

Determination of polyphenol oxidase and peroxidase activities

Extraction of polyphenol oxidase (PPO) and peroxidase (POD) was performed following the methods described by Fukumoto *et al*. (2002) with minor modification. Briefly, fresh or steamed cabbages were cut into thin slices using a stainless steel knife and then chopped using the electric chopper for 1 min. Next, 25 g of the sample was homogenised with 50 mL of chilled 0.05 M phosphate buffer (pH 6.2) and 3.75 g of polyvinylpolypyrolidone (Sigma-Aldrich, St. Louis, MO) using a blender (Waring, model 8011BU, Torrington, CT) at 18,000 rpm for 1 min. The mixture was then filtered through a 425 μm stainless steel screen. The filtrate was centrifuged using a refrigerated centrifuge (Hitachi, Himax CR22 N, Ibaraki, Japan) at 15,000 g at 4°C for 10 min. The supernatant was again filtered through Whatman No. 4 filter paper; the filtrate was kept at 4°C until further analysis.

PPO activity was determined by mixing 50 μL of an enzyme extract with 2.5 mL of 0.05 M catechol (Sigma-Aldrich, St. Louis, MO) and dissolved in 0.05 M phosphate buffer (pH 6.2) in a cuvette at 25 ± 1°C. Next, 50 μL of phosphate buffer (0.05 M, pH 6.2) was used as a reference mixture instead of the enzyme extract. The Parafilm-covered cuvette was inverted three times and the absorbance (410 nm) was measured using a spectrophotometer (Thermo Fisher Scientific, 4001/4 Genesys 20, Fair Lawn, NJ) at every 2 s for a period of 40 s after mixing. The PPO activity was determined from the linear slope of a plot between the absorbance and the reaction time during the first 20 s, which represents the appearance of PPO from the reaction mixture. A unit of activity (U) is defined as an increase of 0.1 absorbance unit per min.

For POD activity determination, a reaction mixture containing 250 μL of an enzyme extract, 2.5 mL of 0.4% (v/v) guaiacol (Thermo Fisher Scientific, Waltham, MA) and 0.4% H2O2 in 0.05 M phosphate buffer (pH 6.2) was prepared in a cuvette at 25 ± 1°C. Next, 250 μL of phosphate buffer (0.05 M, pH 6.2) was used as a reference mixture instead of the enzyme extract. The Parafilm-covered cuvette was inverted three times and the absorbance (470 nm) was measured using a spectrophotometer at every 2 s for a period of 30 s after mixing. The POD activity was determined from the linear slope of a plot between the absorbance and the reaction time for the first 12 s, which represents the appearance of POD from the reaction mixture. A unit of activity (U) is defined as an increase of 0.1 absorbance unit per min.

Determination of myrosinase activity

Myrosinase (MYS) extraction was performed following the methods described by Charron *et al*. (2005) with some modification. Briefly, fresh or steamed cabbages were sliced into small pieces using a stainless steel knife and chopped using the electric chopper for 1 min. The sample (25 g) was then homogenised with 50 mL of chilled 30 mM citrate / phosphate buffer (pH 7) using the blender at 18,000 rpm for 1 min. The mixture was filtered through a 425 μm stainless steel sieve, the filtrate was filled into a 50 mL tube and centrifuged using the refrigerated centrifuge at 30,000 g at 4°C for 4 min. The supernatant was filtered through Whatman No. 1 filter paper and the filtrate was kept at 4°C until further analysis.

Quantification of MYS activity was performed by filling 50 μL of the above-mentioned enzyme extract, 1.35 mL of 32.22 mM citrate / phosphate buffer (pH 6.5) with 1.07 mM EDTA and 100 μL of 37.50 mM sinigrin (Sigma-Aldrich, St. Louis, MO)

into a 5 mL plastic tube and mixed thoroughly at 25 ± 1°C using a vortex mixer (Scientific Industries, model G-560, Bohemia, NY) for 30 s. Next, 100 µL of milli-Q water was used as a reference. The absorbance (at 227 nm) of sinigrin was measured using a spectrophotometer at every 5 s for a period of 5 min. The MYS activity was determined from the linear slope of a plot between the absorbance of sinigrin and the reaction time, which represents the disappearance of sinigrin from the reaction mixture. A unit of activity (U) is defined as a decrease in the absorbance resulting from the hydrolysis of 1 µmol of sinigrin per min.

Determination of glucosinolates profiles

Extraction of glucosinolates (GLSs) was performed following the methods described by Lee *et al*. (2006) with some modification. Briefly, fresh or steamed vegetables were sliced into small pieces using a stainless steel knife and chopped using the electric chopper for 1 min. Fresh or steamed sample (25 g) or cabbage powder sample (0.5 g) was blended with 50 mL of methanol for 1 min, and the mixture was then stirred in a water bath (Major Science, SWB-10L-1, Saratoga, CA) at 70°C for 15 min. The mixture was cooled to room temperature (25°C), filtered through Whatman No. 1 filter paper and washed with 50 mL of methanol. The methanol fraction was dehydrated using a rotary evaporator (Buchi, R-215, Flawil, Switzerland) at 50°C at 100 rpm. The residue was dissolved in 10 mL of methanol and then filled into a centrifuge tube and kept at -18°C until further analysis.

The quantification of GLSs was performed by elimination of the non-GLSs interferences from the crude GLSs extract using Sep-pak® Florisil 6 cc cartridge (Waters, Milford, MA). The activated cartridge was pre-cleaned with 5 mL of 30% (v/v) dichloromethane in hexane. Then, 1 mL of the GLSs extract was injected into the cartridge. Interferences were washed from the cartridge using 5 mL of 30% (v/v) dichloromethane in hexane. GLSs were eluted from the cartridge three times with 5 mL of 30% (v/v) ethyl acetate in methanol. The fraction was evaporated to dryness using a rotary evaporator at 50°C at 100 rpm and the content was reconstituted with 500 µL of HPLC-grade water. The mixture was then filtered through a 0.2 µm nylon filter and was collected for HPLC analysis. Next, 10 µL of the filtrate was injected into Xselect CSH C18 HPLC column (4.6 × 250 mm) (Waters, Milford, MA). Two mobile-phase gradient system of 30 mM ammonium acetate buffer at pH 5 (component A) and methanol (component B) was used. The following gradient elution was used: 100% A - 0% B for 5 min, then increased to 70% A - 30% B from 5 to 25 min and kept at 70% A - 30% B for 5 min. In one min, the elution was back to 100% A - 0% B and kept at 100% A - 0% B for 5 min. The flow rate of the mobile phase was set at 1 mL/min. A UV detector at a wavelength of 233 nm was used for detecting individual GLSs. Individual GLSs contents were determined from standard curves of sinigrin (Sigma-Aldrich, St. Louis, MO), glucoraphanin potassium salt (Chromadex, Irvine, CA), glucoerucin (Chromadex, Irvine, CA), and glucobrassicin (AppliChem, St. Louis, MO). Each standard curve was prepared at the concentrations of 0 - 100 µg/g.

Statistical analysis

The experiments were designed to be completely random. The data were analysed and are presented as mean values with standard deviations. Differences between the mean values were established using Duncan's new multiple range tests. The differences were considered at a confidence level of 95%. All statistical analyses were performed using SPSS® software (version 17, SPSS Inc., Chicago, IL). All experiments were performed at least in duplicate.

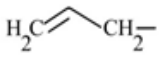
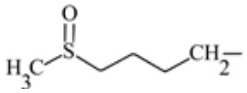
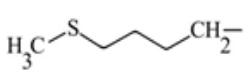
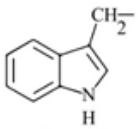
Results and discussion

GLSs profiles of fresh cabbages

GLSs contents in different parts of fresh cabbages are shown in Table 1. The total GLSs contents were calculated as the sum of the four GLSs. Different parts of cabbage head expectedly contained different amounts of individual GLSs. The most abundant GLS was glucoraphanin; significant contents of this GLS were observed in all studied parts of cabbage head. Glucoraphanin contents were within the previously reported range of 167 - 1070 µmol/100 g dry mass (Kushad *et al*., 2004).

Cabbage core was noted to be a rich source of sinigrin; much lower amounts of this GLS were detected in the outer and edible leaves. The opposite trend was found for glucobrassicin; cabbage core contained minute amount of glucobrassicin, while much higher amounts were observed in the outer and edible leaves. Glucoerucin was present in relatively low content in every examined part; the amounts were indeed lower than those reported by other investigators. Kushad *et al*. (2004) and Park *et al*. (2013) reported the glucoerucin contents in white cabbage to be 49 and 69 µmol/100 g dry mass, respectively.

Table 1. Contents of glucosinolates (GLSs) (μmol/100 g DM) in different parts of fresh cabbage.

Common name	Compound group	Chemical name of side chain	Structure of side-chain (R=)	Outer leaves	Edible leaves	Cabbage core
Sinigrin	Aliphatic	2-propenyl		56.10 ± 5.50^{a,A}	68.70 ± 34.00^{a,A}	221.20 ± 11.10^{b,B}
Glucoraphanin	Aliphatic	4-(methylsulfinyl)butyl		485.10 ± 96.00^{c,A}	549.60 ± 87.80^{b,A}	614.70 ± 57.40^{a,A}
Glucoerucin	Aliphatic	4-(methylsulfanyl) butyl		34.90 ± 1.70^{a,A}	40.80 ± 6.60^{a,A}	43.90 ± 15.00^{a,A}
Glucobrassicin	Indole	3-indolylmethyl		282.20 ± 80.40^{b,B}	408.70 ± 65.20^{b,C}	26.80 ± 6.40^{a,A}
			Total	858.30 ± 132.00^{d,A}	1067.80 ± 159.60^{c,A}	906.50 ± 58.70^{c,A}

Data are means ± SD of three replicates (n = 3). DM = dry mass. Different lowercase letters in the same column, and different uppercase letters in the same row indicate significant difference ($p \leq 0.05$).

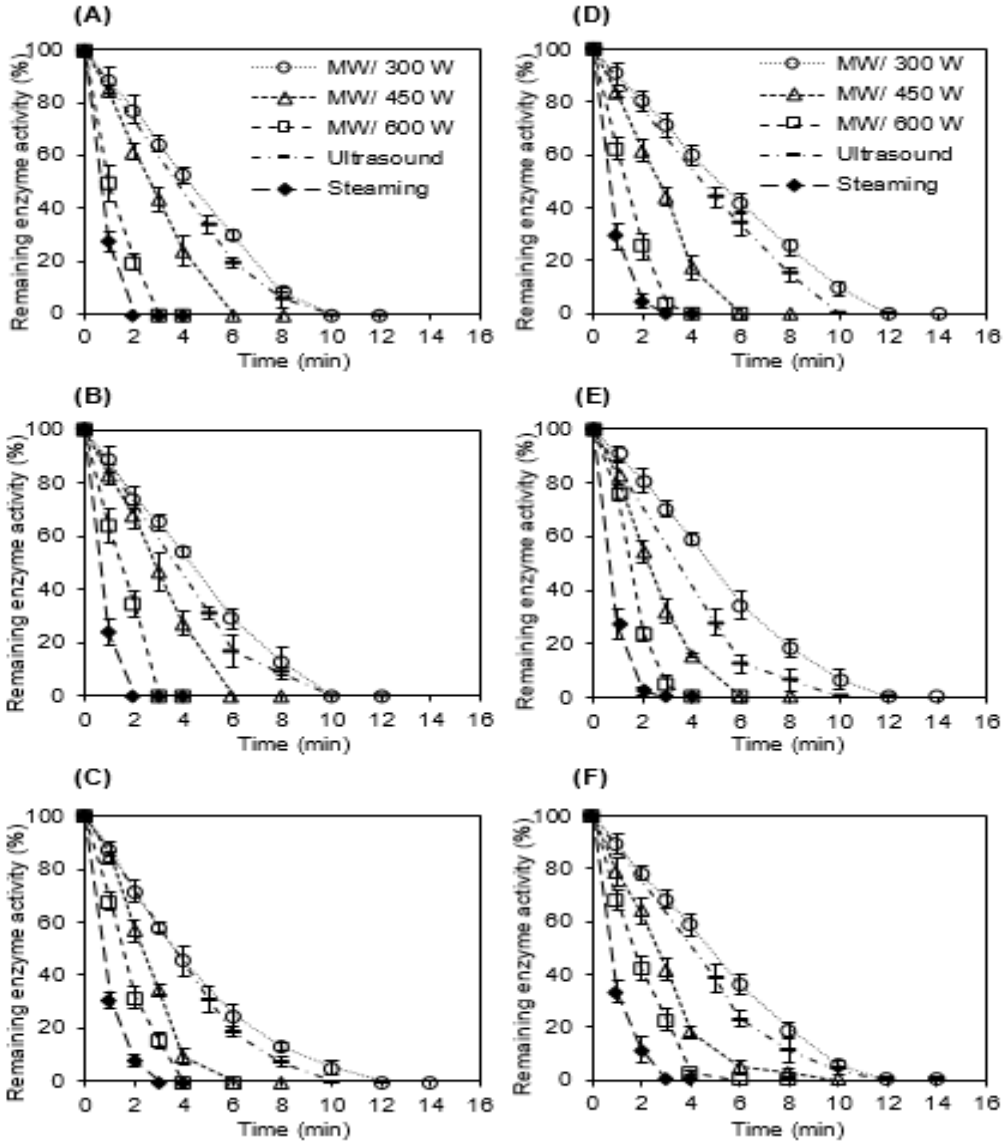


Figure 1. Remaining activities of polyphenol oxidase (A, B, C) and peroxidase (D, E, F) in different parts of cabbage: outer leaves (A, D), edible leaves (B, C), and core (C, F) during blanching by different methods.

Effects of blanching methods and conditions on enzyme activities

The suitable blanching conditions to inactivate PPO and POD were first determined. The activities of PPO in the fresh outer leaves, edible leaves, and core were 158 ± 34, 253 ± 59, and 429 ± 73 U/g fresh mass, respectively, while the activities of POD in the fresh outer leaves, edible leaves, and core were 1,840 ± 249, 2,004 ± 134 and 2,450 ± 287 U/g fresh mass, respectively.

Figure 1 shows the changes in the remaining enzyme activities in different parts of cabbages undergoing different blanching methods. As expected, longer blanching time resulted in more extensive reduction of the enzyme activities. Thermal stabilities of PPO and POD in different parts of cabbages were noted to be different. The enzymes in the cabbage core required longer time to inactivate than those in the outer and edible leaves. This might be because the initial activities of PPO and POD within the core were higher than those of the enzymes within both the outer and edible leaves. Steaming was noted to be the most effective blanching method as it could rapidly inactivate the enzymes. In the case of MAB, subjecting the samples to a higher microwave power accelerated the enzyme inactivation. Nevertheless, MAB at the highest power (600 W) still required longer inactivation time than steaming. Uneven distribution of moisture as well as ions in different parts of the samples led to non-uniform microwave heating (Xiao *et al*., 2017). This could then result in the less effective inactivation of targeted enzymes. Time required by MAB to destroy all the enzymes was then longer. Orak (2006) indeed reported that steaming was a suitable blanching method for POD inactivation in Brassica vegetables when compared with MAB.

USB at the stated condition required shorter inactivation time than MAB at 300 W; such a condition required much longer time than MAB at 450 and 600 W as well as than steaming. The mechanism of enzyme inactivation by ultrasound is acoustic cavitation, which resulted in turn in the generation of thermal, chemical, and mechanical effects, leading eventually to enzyme inactivation (Mawson *et al*., 2011).

Table 2 summarises the time required to steam blanch cabbage samples to inactivate the three enzymes, namely, PPO, POD, and MYS. The results showed that the steaming condition that can be used to inactivate PPO and POD was also sufficient to completely inactivate MYS. Based on all the above results, the suitable time for steam blanching outer leaves, edible leaves and core of white cabbage is 3 min.

Effects of blanching and drying on GLSs profiles

Evolutions of individual GLSs during steam blanching and drying were investigated. Steam blanching was selected as an appropriate treatment prior to drying as this method required the shortest time and exhibited only minute effect on GLSs.

The contents of individual GLSs in different parts of cabbage after steam blanching and drying are shown in Figure 2. Steam blanching led to no significant losses of GLSs. This is quite different from the case of water blanching where it has been reported that GLSs in Brassica vegetable significantly decreased

Table 2. Remaining activities of polyphenol oxidase, peroxidase and myrosinase in different parts of steamed blanched cabbage.

Part of cabbage	Steam blanching time (min)	Remaining activity (%)		
		Polyphenol oxidase	Peroxidase	Myrosinase
Outer leaves	Fresh	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00
	1	4.26 ± 1.27	17.73 ± 2.89	13.30 ± 2.94
	2	n.d.	1.19 ± 0.77	4.75 ± 2.30
	3	n.d.	n.d.	n.d.
Edible leaves	Fresh	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00
	1	7.26 ± 2.09	16.89 ± 6.65	14.33 ± 3.10
	2	n.d.	2.20 ± 1.22	5.17 ± 0.48
	3	n.d.	n.d.	n.d.
Cabbage core	Fresh	100.00 ± 0.00	100.00 ± 0.00	100.00 ± 0.00
	1	21.89 ± 7.77	30.05 ± 3.35	21.51 ± 0.95
	2	1.92 ± 1.53	2.75 ± 1.09	6.15 ± 0.42
	3	n.d.	n.d.	n.d.

Data are means ± SD of three replicates (n = 3). n.d. = not detected.

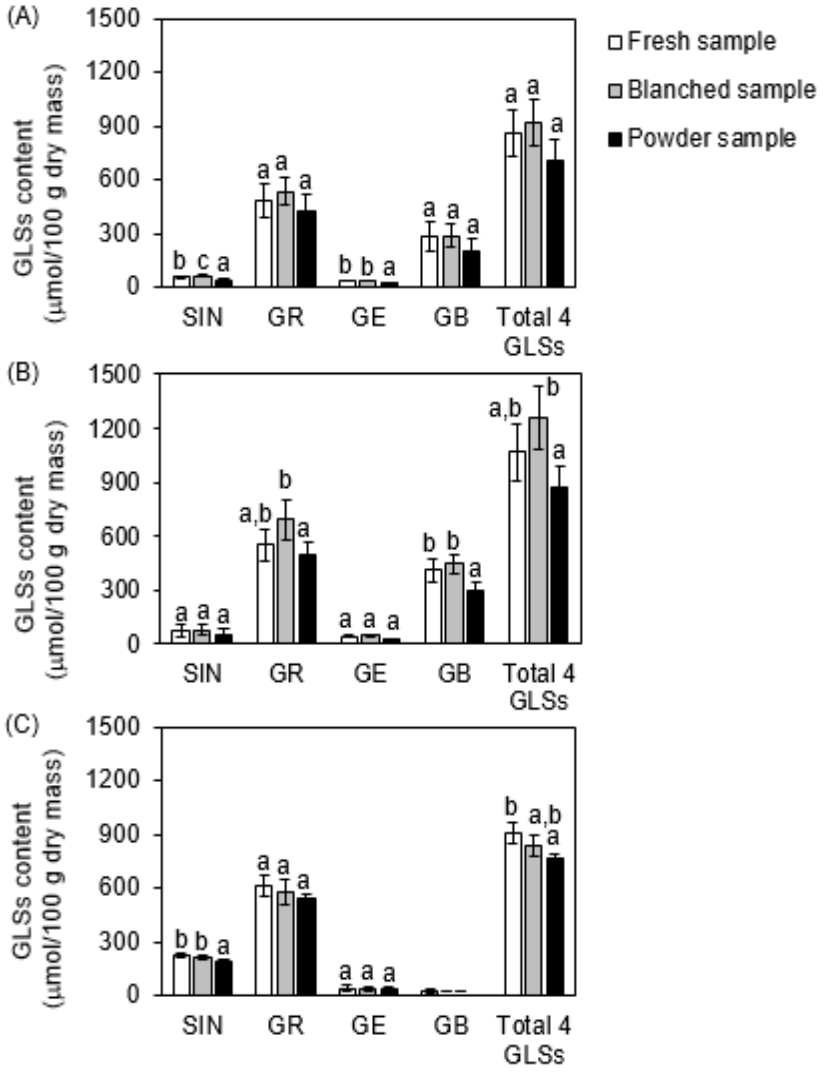


Figure 2. Contents of glucosinolates (GLSs) in different parts of cabbage: (A) outer leaves, (B) edible leaves, and (C) core during preparation into vegetable powder. The measured GLSs are sinigrin (SIN), glucoraphanin (GR), glucoerucin (GE), and glucobrassicin (GB). Total GLSs are the sum of the four measured GLSs. Different letters over the bars belonging to the same GLSs indicate significant difference ($p \leq 0.05$).

(Wennberg *et al*., 2006; Volden *et al*., 2008). Results that are similar to those of our work were reported by Song and Thornalley (2007). The study reported that steam blanching for 20 min had little effect on GLSs contents of broccoli, Brussel sprout, cauliflower, and green cabbage. Glucobrassicin in cabbage core was not detected after steam blanching, which could be due to the fact that glucobrassicin was only found in small amount (26.8 µmol/g dry mass) and might have degraded during steaming.

Reduction in the GLSs contents was observed after drying. Earlier works also reported that drying, especially at a higher temperature, caused a significant reduction in GLSs. Chaisamlitpol *et al*. (2014) reported that GLSs in white cabbage undergoing drying started to degrade at around 70°C. In the present work, there was only a short period of time that the sample temperature exceeded 70°C. The degradation of GLSs was then expected to take place only for a shorter period of time. The decrease in GLSs in our samples was therefore not extensive.

The overall retention of GLSs in the vegetable powder produced from three different parts of white cabbage is given in Table 3. The retention of GLSs in the powder was in the range of 82 - 84% (or 16 - 18% loss). The losses of GLSs in the vegetable powder were lower than those reported by Buachap (2015). In that work, approximately 19 - 33% of the total GLSs was degraded during the production of vegetable powder from Thai Brassica vegetables (namely, Chinese cabbage, Chinese kale, and Chinese mustard). The vegetable powder produced in that previous work also underwent steam blanching and hot air drying at 60 - 80°C. Our results clearly demonstrated that different types of GLSs and even the same GLSs in different vegetables possess

Table 3. Overall retention of glucosinolates (GLSs) in cabbage powder.

Part of cabbage	GLS	GLSs content (μmol/100 g DM)		Retention (%)
		Fresh sample	Powder sample	
Outer leaves	SIN	56.10 ± 5.50	43.40 ± 3.60	77.50 ± 3.30^{a,b}
	GR	485.10 ± 96.00	431.50 ± 84.50	89.00 ± 2.50^{c}
	GE	34.90 ± 1.70	25.70 ± 1.50	73.60 ± 4.70^{a}
	GB	282.20 ± 80.30	205.10 ± 71.40	71.80 ± 4.90^{a}
	Total	858.30 ± 132.00	705.60 ± 122.00	82.00 ± 2.10^{b}
Edible leaves	SIN	68.70 ± 34.00	51.70 ± 26.20	75.50 ± 4.40^{b}
	GR	549.60 ± 87.80	494.40 ± 72.70	90.10 ± 1.60^{d}
	GE	40.80 ± 6.60	27.70 ± 2.70	68.30 ± 4.80^{a}
	GB	408.70 ± 65.20	300.00 ± 45.30	73.50 ± 1.50^{a,b}
	Total	1067.80 ± 159.60	873.70 ± 118.30	81.90 ± 1.30^{c}
Cabbage core	SIN	221.20 ± 11.10	187.20 ± 11.20	84.60 ± 2.40^{c}
	GR	614.70 ± 57.40	540.90 ± 26.30	88.30 ± 4.90^{c}
	GE	43.90 ± 15.00	34.20 ± 13.20	77.20 ± 3.40^{b}
	GB	26.80 ± 6.40	n.d.	0.00 ± 0.00^{a}
	Total	906.50 ± 58.70	762.30 ± 28.30	84.20 ± 2.90^{c}

Data are means ± SD of three replicates (n = 3). n.d. = not detected. DM = dry mass. Different lowercase letters in the same column belonging to the same part of cabbage indicate significant difference ($p \leq 0.05$). % Retention = $(C/C_0) \times 100$, where C is GLSs content in powder sample and C_0 is GLSs content in fresh sample. SIN = sinigrin; GR = glucoraphanin; GE = glucoerucin; GB = glucobrassicin.

different thermal stabilities. Our findings also imply that the thermal stabilities of GLSs in white cabbage are higher than those found in the aforementioned Thai Brassica vegetables.

The results further illustrated that glucobrassicin was the most vulnerable GLS to thermal processing. The results reported here are consistent with those reported in the previous studies. Ciska and Kozłowska (2001) and Oerlemans *et al*. (2006) found that glucobrassicin, which is an indole GLS, was more sensitive to heat than aliphatic GLSs, including sinigrin and glucoraphanin. Among the three aliphatic GLSs, glucoraphanin exhibited the highest thermal stability (Table 3). This could be due to the chemical structure of glucoraphanin. Methylsulfinyl GLSs (e.g., glucoraphanin) are generally more stable than methylsulfanyl GLSs (e.g., glucoerucin) (Hanschen *et al*., 2012).

Conclusion

The profiles of important GLSs in different parts of white cabbage were investigated. The total GLS contents in outer leaves and core were comparable to that in edible leaves. These three cabbage parts could therefore be used as a raw material to produce vegetable powder containing GLSs. Steam blanching is suggested as a suitable pre-treatment among the other methods tested in the present work since it required the shortest time and exhibited only minute effect on the GLSs contents. Drying was noted, on the other hand, to be a major processing step affecting the GLSs. Steam blanching for 3 min followed by hot air drying at 80°C is recommended for the production of GLSs-rich vegetable powder from white cabbage. The powder underwent such procedures contained approximately 82 - 84% of GLSs in the fresh vegetables. The release kinetics of GLSs from the vegetable powder during digestion is suggested as a future work.

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