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Quality of cabbage during long term steaming; phytochemical, texture and colour evaluation

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ABSTRACT

Steaming has been reported to better retain the glucosinolate (GS) content in *Brassica* vegetables than boiling. However, there is little information on the GS content, colour, and texture attributes in *Brassica* vegetables in relation to the duration of steaming. This study investigated the effect of the duration of steaming, which was applied in certain commercial preparation processes, on the GS content, colour, and texture of white cabbage. Results showed that the total accessible content of GSs increases initially during steaming until 10 min followed by a consistent decline up to 180 min. This observed initial increase is mainly due to the content of aliphatic GSs rather than indole GSs, which tend to decrease from the start of steaming. A mathematic model for the observed behaviour of the GSs, taking into account several mechanisms, is proposed and fitted to the data. The intensity of the green colour of the cabbage slightly increased during the first 15 min of steaming followed by a decrease onwards. The hardness showed a continuous decline during the entire steaming duration. The study indicates that steaming up to 10 min could promote the health properties as well as the colour and texture attributes of steamed cabbage.

1. Introduction

Intake of *Brassica* vegetables has been inversely associated with the risk of lung, colorectal, and prostate cancer (Higdon, Delage, Williams, & Dashwood, 2007; Kristal & Lampe, 2002). Several conversion products of glucosinolates (GSs), found almost exclusively in *Brassica* vegetables, are showing biological activities in the human body that are assumed to be responsible for reducing this risk of several cancers (Verhoeven, Verhagen, Goldbohm, van den Brandt, & van Poppel, 1997). In intact plant tissue, GSs are stored in separate compartments from the enzyme myrosinase (thioglucosidase EC 3.2.1.147). However, upon the plant tissue disruption, GSs are highly prone to hydrolytic degradation catalysed by the enzyme (Fahey, Zalcmann, & Talalay, 2001; Mithen, Dekker, Verkerk, Rabot, & Johnson, 2000). Among the breakdown products of the GSs, isothiocyanates have been reported to inhibit phase 1 and to induce phase 2 enzymes that are beneficial with respect to (pro)carcinogen metabolism and excretion (Traka & Mithen, 2009).

GSs are water-soluble compounds that may leach into cooking water during vegetable preparation. For example, boiling of *Brassica* vegetables results in 25%–75% decreases in total GS content (Nugrahedi, Verkerk, Widianarko, & Dekker, 2015). Cooking methods that use less water, such as steaming and microwaving, have shown to reduce GS losses (Rungapamestry, Duncan, Fuller, & Ratcliffe, 2006; Song & Thornalley, 2007; Vallejo, Tomas-Barberan, & Garcia-Viguera, 2002; Verkerk & Dekker, 2004). Several types of processing of *Brassica* vegetables have been studied and many have a pronounced impact on the concentration of GSs and their corresponding isothiocyanates (Verkerk et al., 2009). The observed effects can be explained by multiple mechanisms such as i) myrosinase inactivation, ii) cell lysis and leaching of GSs, breakdown products, and myrosinase in the cooking water, and iii) thermal degradation of GSs (Nugrahedi et al., 2015).

Often, these studies describe various cooking procedures based on the dietary habits and cuisines in the western society. While

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List of abbreviations (variables) used in the equations

$C_{g,w}$	Concentration of GSs in the free water (μmol/g) on/in the cabbage rolls
$C_{g,v}$	Concentration of GSs in the intact part of the vegetable (μmol/g)
$C_{gv,\ measured}$	Concentration of GSs in the intact vegetable tissue that is available for the extraction (μmol/g)
$C_{g,\ measured}$	Concentration of GSs as measured in a sample of the cabbage rolls (in the lysed part as well as in the intact tissue part) (μmol/g)
F_i	Fraction of intact cells
$F_{GS\text{-}trapped}$	Fraction of the total vegetable weight
F_{con}	Fraction of the condensed steam (free of GSs)
k_l	Rate constant of cell lysis (min^{-1})
k_{wg}	Rate constant of cell lysis (min^{-1})
$k_{d,w}$	Breakdown rate constant of GSs in the free water pool (min^{-1})
k_T	Rate constant of temperature increase due to steaming (min^{-1})
$M\_veg_{inaccessible}$	Mass of the vegetable containing trapped GSs that is not available for the extraction (g)
M_veg_{total}	*Total* mass of the intact vegetable tissue (g)
M_C	Mass of condensed steam (g) on/in cabbage rolls
$M_{C,final}$	Final (steady state) mass of condensed steam (g) on/in cabbage roll
M_L	Mass of lysed cell content (g)
M_w	Mass of free water (g) consisting of the condensate mass and the lysed cell mass
$M_{v,0}$	Initial mass of vegetable (g)
T	Absolute temperature (K)
T_{final}	Final temperature reached during steaming
t_n	Time n; steaming for time of n min
t_0	Time 0; initial time when steaming is started
$\|L$	Change of GSs due to leaching
$\|D$	Change of GSs due to condensation of steam and drip-flow of condensate
$\|C$	Change of GSs due to absorbed condensate mass on/in the cabbage rolls
$\|B$	Change of GSs in the condensate due to thermal breakdown

studies on Asian preparation methods of *Brassica* vegetables and the effects on phytochemical content have been underexposed. Probably the processes and underlying mechanisms responsible for GS losses are similar for different cuisines, however the extend of losses can vary based on different characteristics of Asian vegetable preparation methods and the use of different vegetable-based products in the Asian cuisine.

Steaming has been reported to better retain the GS content in *Brassica* vegetables than boiling and blanching (Miglio, Chiavaro, Visconti, Fogliano, & Pellegrini, 2008; Rungapamestry et al., 2006; Volden, Borge, Hansen, Wicklund, & Bengtsson, 2009). However, steaming of *Brassica* vegetables extensively for long times, could result in substantial losses of GSs differently from short steaming processes reported in literature thus far. An example product using long steaming times is cabbage roll, a typical Asian dish made from shortly blanched leaves of white cabbage that are folded and rolled, and subsequently steamed. Steamed cabbage roll is usually served as a kind of dim sum, which includes also e.g.: boiled potato and tofu. The product is produced and sold generally by street- or mobile-vendors (Tan, 2002). During selling, the rolls can be steamed constantly for more than 2 h, depending on the selling rate, on a very low flame level. To our knowledge, there is little information on the behaviour of GSs in *Brassica* vegetables in relation to the long duration of steaming (Song & Thornalley, 2007; Verkerk, Knol, & Dekker, 2010).

In order to understand and simulate the changes of concentration of GSs as affected by processing, previous studies employed kinetic modelling to describe and predict these changes. Leaching and thermal degradation are the main mechanisms affecting GS changes since myrosinase is a thermolabile enzyme and is inactivated early in most thermal processes (Hennig, Verkerk, Bonnema, & Dekker, 2012; Sarvan, Verkerk, & Dekker, 2012; Sarvan, Verkerk, van Boekel, & Dekker, 2014).

Next to these effects of the process on the GS content and subsequent health value, colour and texture are the important sensorial attributes perceived by the consumers to evaluate the quality of both fresh and cooked vegetables (Jackman & Stanley, 1995; Miglio et al., 2008; Nisha, Singhal, & Pandit, 2004). The degree of greenness is an important colour quality attribute of thermally processed green vegetables. The changes of hardness, softness, or firmness can be expressed as important textural quality attributes of vegetables.

The present study aims to investigate the effect of a long duration of steaming on the GS content, colour, and texture of the cabbage roll. In addition the changes of GSs during steaming are also mathematically modelled to gain insight in the important mechanisms involved. In the societal context this study will be beneficial to know the changes of the health-promoting and physical quality attributes of vegetable products and to optimise real preparation methods commonly employed by especially Asian food service establishments.

2. Materials and methods

2.1. Sample preparation

Two batches of raw white cabbages (*Brassica oleracea* L. Capitata) were collected from one local supplier in Semarang, Indonesia on two consecutive days. Six heads of white cabbage were used in each experimental batch. Damaged outer leaf layers of the cabbage heads were removed. Leaf layers of the white cabbage from the surface until about half diameter of the head were taken, washed by running tap water and drained.

2.2. Blanching and steaming

The preparation and processing method of the cabbage rolls was performed in triplicate by mimicking the common practice of the small-scale food service establishments in Semarang, Indonesia. Heat was provided by using a liquefied petroleum gas stove (Rinnai RI-602E, gas consumption = 2.9 kW). Briefly, leaves of white cabbage were blanched in the distilled water at the ratio of 1:6 (kg:L) for 3 min in an open aluminium pan. Then, each leaf was rolled manually resulting in a cabbage roll at the diameter of about 3 cm and the length of about 7 cm. Each roll was made from about 35 g fresh leaves. Each batch of processing took about 5 min for rolling all the cabbage leaves.

Subsequently, all rolls (total weight approximately 2 kg) were steamed in a closed steaming pan containing boiling water for 180 min, comparable with the artisanal procedure often applied in

Asian food service establishments. The rolls were arranged in two layers in a way that the steam can still reach the lid. The flame was maintained at the lowest level during steaming resulting in gentle boiling of the water. The number of the rolls in the steaming pan was twice of the number of samples needed for each batch analysis and sample rolls were taken randomly only from the top layer of rolls at certain time-points of steaming until 180 min. The analyses of GSs, colour, and texture were performed on separate rolls.

2.3. Glucosinolate analysis

Three leaves of raw, or rolls of blanched and steamed cabbage were chopped into pieces and directly frozen in liquid nitrogen followed by frozen grinding in a stainless steel blender (Waring 2-speed EW 04242-11) and storing at −20 °C until lyophilisation for 5 days (Heto Power Dry LL1500, Thermo Scientific). The sample of the steaming water was prepared by freezing 10 mL of the water in liquid nitrogen followed by storing it in the freezer at −20 °C until further analysis.

2.3.1. Extraction and desulphation

The extraction method of GSs in the cabbage used hot methanol as the solvent followed by on-column desulphation as described by Verkerk, Dekker, and Jongen (2001) with slight modifications, *i.e.* fivefold downscaling the mass and volume during extraction and centrifuging at 3500 × g following incubation.

2.3.2. HPLC analysis

HPLC set-up used a Shimadzu LC 10 Avp with a manual injection system (Rheodyne 7725i). A UV Vis detector (SPD 10 Avp) was performed at a wavelength of 229 nm. The de-sulpho-GSs were separated by using a GraceSmart RP-18 5μ column. The elution was performed by the gradient system of water containing 0.05% tetramethyl ammonium chloride and acetonitrile/water (40:60, mL:mL) containing 0.05% tetra-methyl ammonium chloride. The flow rate, total elution time, and gradient flow followed Verkerk et al. (2001). The GSs were identified by comparing with standards of sinigrin and comparison with the chromatograms of reference materials (broccoli, cauliflower, red cabbage, radish, and *Brussels* sprouts) with known GS profiles, as well as confirming with data from literature. Each GS was quantified using the published response factors against glucotropaeolin as internal standard. The total GS concentration was determined by adding up all individual GS (Verkerk et al., 2001).

2.4. Colour

Colour of the samples was recorded as the colour coordinates L^*, a^*, b^* by a chromameter CR 400 (Konica Minolta). The instrument was calibrated before each series of measurements using the standard white tile ($L^* = 97.39$, $a^* = 0.02$, and $b^* = 1.69$). Colour of the cabbage roll was measured at the surface of the roll laid down on the white tile while the fresh sample was measured as leave. Triplicate samples of each treatment were taken from each experimental batch. Each roll was measured in duplicate at different locations. The ratio $-a^*/b^*$ was calculated to represent the greenness of the cabbage (Tijskens, Schijvens, & Biekman, 2001).

2.5. Texture

Six cabbage rolls of each treatment were taken from each experimental batch. Each roll was placed on the base table and measured once at the middle of its longitudinal axis. A texture analyser (TAPlus, Lloyd) was used to examine the hardness value, *i.e.* the peak force of the first compression cycle during the measurement. The analysis was performed by a compression test to the cabbage roll until 25% of the original thickness by using a 25 mm cylinder probe and the speed at 5 mm/s (modified from Christiaens et al., 2011). The percentage of softening was calculated as:

Softening (%) = (1 − (maximum force of steamed sample at t_n/maximum force of steamed sample at t_0)) × 100% (modified from Miglio et al., 2008).

2.6. Kinetic modelling of GS content during steaming

The changes of GS content of the cabbage rolls during steaming can be influenced by the following mechanisms:

1. Cell lysis;
2. Enzymatic hydrolysis by endogenous myrosinase;
3. Myrosinase inactivation;
4. Increase in extractability of GSs;
5. GS thermal breakdown;
6. Steam condensation on the rolls;
7. GS leaching to the condense water on/in the rolls;
8. Condense water containing GSs dripping from the rolls.

The mechanisms 1, 5, and 7 are modelled according to the equations as previously published for general thermal processing of *Brassica* vegetables by Sarvan et al. (2012). The changes due to mechanisms 2 and 3 are assumed to be negligible due to the fast inactivation of myrosinase during the relatively short heat-up phase during the blanching pretreatment of the cabbage. The modelling of mechanism 4 is discussed in Section 2.6.2, mechanisms 6–8 are discussed in Section 2.6.3.

2.6.1. Heating up of the cabbage rolls

The measurements of the temperature of the cabbage rolls could be described by an asymptotic increase until the final temperature of 373 K was reached, by the following equation:

$$\frac{dT}{dt} = k_T \cdot \left(T_{final} - T\right) \quad (1)$$

In Fig. 1 the vegetable tissue is shown schematically as it is build-up of the different compartments and how they are described by the model equations below.

2.6.2. Increased extractability

The increased extractability (mechanism 4) is assumed to be caused by the fact that a part of the GSs is located in a fraction of the vegetable tissue that is not available for the extraction procedure (a

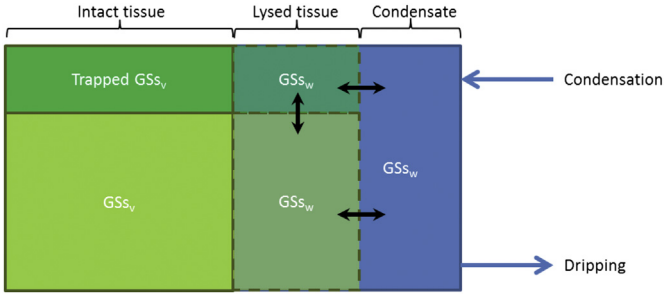

Fig. 1. Schedule of the vegetable tissue during steaming consisting of different compartments. When analysing the GS concentration in the vegetable samples the trapped GSs$_v$ are not detected (GSs$_v$ = Glucosinolates in the vegetable, GSs$_w$ = Glucosinolates in the water or condensate).

so-called "trapped GSs$_v$" in Fig. 1). The lysis of cells in this fraction (expressed as a fraction of the total vegetable weight: $F_{GS\text{-}trapped}$) is assumed to follow the same kinetics as the cell lysis of the other cells, in order to not have an additional parameter to be estimated from the data. So when cell lysis occurs the measured GS content is increasing due to this mechanism, a phenomena that is often described in literature (Gliszczyñska-šwiglo et al., 2006; Miglio et al., 2008; Oerlemans, Barrett, Suades, Verkerk, & Dekker, 2006; Verkerk & Dekker, 2004). Upon cell lysis the GSs are no longer part of the intact tissue but become part of the lysed tissue that is assumed to partition to the condensate water outside the rolls (GSs$_w$).

$$F_{GS-trapped} = M\_veg_{inaccessible}/M\_veg_{total} \quad (2)$$

$$C_{gv,measured} = \left(1 - F_{GS-trapped}\right)\cdot C_{gv} \quad (3)$$

2.6.3. Steam condensation and dripping

Steam will condensate on the cabbage rolls and part of this condensate will be absorbed by the rolls (mechanism 6 and Fig. 1). The amount of condensed steam on/in the cabbage rolls is measured by weighing the rolls during the 3 h steaming process. It was observed that the weight gradually increased until a maximum of on average 18% weight gain relative to the starting weight of the vegetable rolls (data not shown). This condensate absorption by the rolls is modelled by the following equation:

$$\frac{dM_C}{dt} = k_{wg}\cdot\left(M_{C,\,final} - M_C\right) \quad (4)$$

Also the lysed part of the vegetable tissue will increase in time (Sarvan et al., 2012) and can be described by:

$$\frac{dM_L}{dt} = -\frac{dF_i}{dt}M_{v,0} = k_l\cdot F_i\cdot M_{v,0} \quad (5)$$

The mass total 'free' water is the sum of the condensate mass and the lysed cell mass:

$$M_w = M_C + M_L \quad (6)$$

The concentration of GSs in the total free water mass on/in the cabbage rolls is described by four processes:

1. The increase by GSs leaching from lysed accessible and inaccessible (trapped GSs) cells (L)
2. The decrease by the condensation of steam (free of GSs) and the drip-flow of condensate, containing GSs (D)
3. The decrease by the increasing absorbed condensate mass on/in the rolls (C)
4. The decrease by thermal breakdown of GSs present in the condensate (B)

$$\frac{dC_{g,w}}{dt}\Big|L = \frac{k_l\cdot F_i\cdot M_{v,0}}{\left(1 - F_{GS-trapped}\right)}\cdot\frac{\left(C_{g,v} - C_{g,w}\right)}{M_w} \quad (7)$$

$$\frac{dC_{g,w}}{dt}\Big|D = -F_{con}\cdot\frac{C_{g,w}}{M_w} \quad (8)$$

$$\frac{dC_{g,w}}{dt}\Big|C = -\frac{C_{g,w}}{M_w}\cdot\frac{dM_C}{dt} = -\frac{C_{g,w}}{M_w}\cdot k_{wg}\cdot\left(M_{C,\,final} - M_C\right) \quad (9)$$

$$\frac{dC_{g,w}}{dt}\Big|B = -k_{d,w}\cdot C_{g,w} \quad (10)$$

The resulting change in time of this GS concentration in the water phase is the sum of these four equations.

The GS concentration in the intact vegetable cells (accessible and trapped), $C_{g,v}$, is described by a first order degradation reaction (Sarvan et al., 2012).

2.6.4. Measured GS concentration in the cabbage rolls

The measured GS concentration in the cabbage rolls is the sum of the measurable amount of GSs in the intact vegetable cells plus the GSs in the lysed vegetable cells and in the condensate in/on the rolls divided by the total mass of the rolls, which is the mass of cabbage plus the mass of condensate:

$$C_{g,\,measured} = \frac{\left\{\left(1 - F_{GS-trapped}\right)\cdot F_i\cdot C_{g,v}\cdot M_{v,0}\right\} + \left\{C_{g,w}\cdot\left(\left(1 - F_i\right)\cdot M_{v,0} + M_C\right)\right\}}{\left(M_{v,0} + M_C\right)} \quad (11)$$

The model calculates the concentration of GSs expressed as μmol/100 g FW. Meanwhile, the samples are measured as μmol/100 g DW. To convert the FW concentrations to the DW the weight increase of the additional condensation water is taken into account to convert the model predictions into a concentration expressed as μmol/100 g DW. The initial DW% of the vegetable mass (so before the uptake of condensate) is assumed to be 10 g/100 g. Additional soluble solid loss from the vegetable during steaming was assumed to be negligible.

2.7. Data analysis

Numerical integration of the equations and parameter estimation of the rate constants followed the procedure described by Sarvan et al. (2012) by using software package Athena Visual Workbench (www.athenavisual.com).

3. Results and discussion

3.1. Glucosinolates of raw white cabbage

Five GSs were identified in the raw white cabbage: glucoiberin, glucoraphanin, gluconapin, glucobrassicin, and 4-methoxyglucobrassicin (Table 1). The aliphatic GSs were the most dominant with 60% of the total concentration, and glucoraphanin as the major constituent at 37% of the total GSs. Indoles accounted for the other 40% with glucobrassicin as the most prominent (37% of total GSs).

Table 1
Glucosinolate concentration (μmol/100 g DW) in white cabbage.

Glucosinolate	Raw	Blanched
Glucoiberin	246.49 ± 43.72	337.96 ± 86.89
Glucoraphanin	475.90 ± 86.11	566.90 ± 162.10
Gluconapin	42.21 ± 7.27	91.50 ± 28.98
Glucobrassicin	474.17 ± 239.54	497.86 ± 133.45
4-Methoxy-glucobrassicin	36.39 ± 6.57	45.61 ± 19.28
Total GSs	1275.15	1539.82

Values are presented as means ± standard deviations ($n = 6$).

This GS composition is comparable to previous studies on white cabbage, although some studies report the sinigrin content of white cabbage to be higher compared to the glucoraphanin content (Ciska & Kozłowska, 2001; Ciska & Pathak, 2004; Fuller et al., 2007; Song & Thornalley, 2007; Wennberg, Ekvall, Olsson, & Nyman, 2006). The differences in the sinigrin/raphanin content described in literature could be due to the differences in the cultivar and cultivation conditions that are known to affect the GS profile and content substantially (Ciska, Martyniak-Przybyszewska, & Kozlowska, 2000; Kang, Ibrahim, Juvik, Kim, & Kang, 2006; Krumbein, Schonhof, & Schreiner, 2005).

3.2. Glucosinolates of cabbage roll

Blanching of the cabbage leaves for 3 min, as first step in the procedure of cabbage roll preparation, led on average to an increase of 21% of total GSs compared with the raw cabbage (Table 1). Both, the processing conditions and the *Brassica* vegetable type can influence the behaviour of GSs upon heating. Some studies reported that boiling can increase the GS concentration in *Brassica* vegetables. Usually this is observed at short heat treatments, and ascribed to a higher extractability of GSs in the boiled tissues (D'Antuono, Elementi, & Neri, 2007; Fuller et al., 2007; Rungapamestry, Duncan, Fuller, & Ratcliffe, 2008). However, extensive boiling was generally reported to considerably reduce GS content of *Brassica* vegetables even to more than 50% of the raw material (Gliszczyńska-świglo et al., 2006; Miglio et al., 2008; Song & Thornalley, 2007; Vallejo et al., 2002). Extensive leaching and thermal degradation of GSs was indicated as the major contributors to the losses (Francisco, Velasco, Moreno, Garcia-Viguera, & Cartea, 2010; Nugrahedi et al., 2015; Volden et al., 2009).

The total GS content after blanching was relative stable during the first 10 min of steaming (Fig. 2). Subsequent steaming of the cabbage rolls led to a gradual decrease of 66% in total GS content after 180 min. A marked difference in behaviour was observed between aliphatic and indole GSs; about 54% of total aliphatic GSs were lost, while more than 90% of total indole GSs of the blanched cabbage rolls was lost after steaming for 180 min. It can be assumed that the hydrolytic enzyme myrosinase had been inactivated by the blanching step prior to steaming, so the decrease in GS content will be mainly caused by leaching and thermal degradation. Verkerk et al. (2010) reported that the total GS content in steamed broccoli, as compared with the untreated broccoli, was up to 55% higher after about 10 min and approximately 4% lower levels after 30 min of steaming. Meanwhile, Song and Thornalley (2007) reported no significant losses of total GSs in broccoli, green cabbage, cauliflower, and *Brussels* sprout over 20 min of steaming. Moreover, after 30 min steaming of broccoli substantial losses of total indole GSs (55%) and less loss of total aliphatic GSs (8.5%) were observed (Verkerk et al., 2010), confirming the present observation that indole GSs are less retained during steaming than the aliphatic GSs.

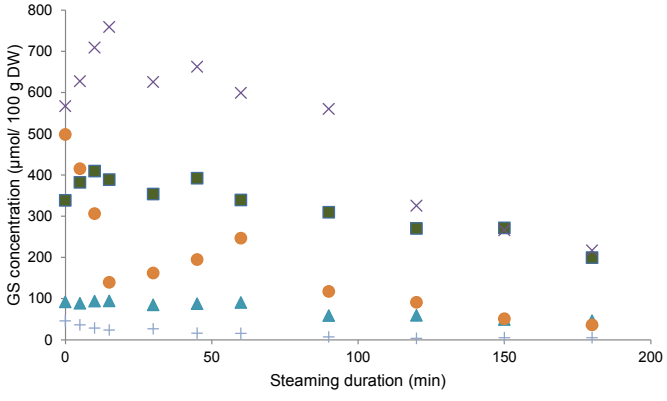

Fig. 2. Glucosinolate concentration (μmol/100 g DW) along the production of cabbage roll ($n = 6$) (symbols □: Glucoiberin, ○: Glucobrassicin, Δ: Gluconapin, ×: Glucoraphanin, +: 4-Methoxy-glucobrassicin).

One of the possible causes of GS losses during longer steaming duration could be thermal degradation of GSs (Verkerk et al., 2010). Nevertheless, the heating rate of the vegetable tissue is generally lower in steaming compared to boiling. Moreover, since there is no direct contact between the vegetable tissue and a large pool of water, steaming is expected to result in less leaching compared to boiling (Nugrahedi et al., 2015). Nevertheless, losses by leaching into the condensed steam followed by drip loss can still be an important loss mechanism in (long term) steaming. Shorter steaming times have been reported to have benefits over longer ones in terms of better retaining the GSs (Galgano, Favati, Caruso, Pietrafesa, & Natella, 2007; Miglio et al., 2008).

3.3. Mathematical modelling of glucosinolate changes during steaming

3.3.1. Parameter estimation for glucoraphanin

The complete model description as described above consists of many parameters. In order to reduce the number of parameters to be estimated from the current experimental data, some parameter estimates have been taken from literature (Sarvan et al., 2012, 2014; Volden, Wicklund, Verkerk, & Dekker, 2008). Table 2 shows the parameter estimates and their standard deviations during the steaming experiment. Two parameters (k_{Temp} and k_{wg}) were estimated from the measurements of the temperature and weight increase of the rolls during the steaming experiments. Three parameters were estimated from the experimental GS data, *i.e.*: $C_{g,v}$, $F_{GS\text{-}trapped}$ and F_{con}.

Fig. 3 shows the experimental data with the model description for glucoraphanin. The model fits the observed concentration profile of glucoraphanin during the steaming duration. The model fit had an r^2 of 0.88 and the residuals show a homoscedastic distribution over the time course.

Table 2
Parameter estimates during the steaming experiment.

Parameter	Value	SD	Reference
$k_{L,100\ °C}$	0.11 min^{-1}		Sarvan et al. (2012)
Ea_k_L	53 kJ/mol		Sarvan et al. (2012)
$k_{dv,100\ °C\ raphanin}$	5.9 10^{-3} min^{-1}		Sarvan et al. (2014)
$Ea\_k_{dv,100\ °C\ raphanin}$	93 kJ/mol		Sarvan et al. (2014)
$k_{dw,100\ °C\ raphanin}$	6.8 10^{-3} min^{-1}		Volden et al. (2008)
$Ea\_k_{dw,100\ °C\ raphanin}$	93 kJ/mol		Sarvan et al. (2014)
k_{Temp}	0.12 min^{-1}		
k_{wg}	0.03 min^{-1}		
$C_{g,v}$ (μmol/100 g DW)	637	34	
$F_{GS\text{-}trapped}$ (−)	0.22	0.09	
F_{con} (g/min)	0.028	0.030	

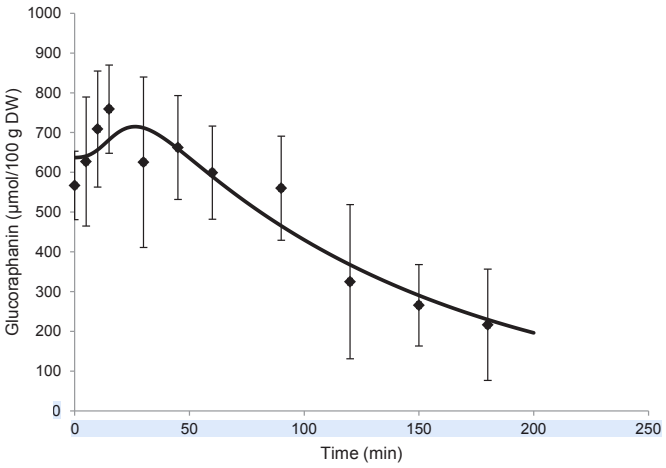

Fig. 3. Experimental data (symbols) and model description (line) of the glucoraphanin content during long term steaming.

The estimated values of the condensate/drip flow seems to be very low. Based on measurements of water evaporation rate (around 1.5 g/min) a much higher value would be expected. Not all the evaporated water is expected to condensate on the vegetable rolls since most of the steam will condense on the wall and lid of the pan. But the value of F_{con} corresponds to only 2% of the evaporated water flow, which is lower than expected. This is most likely caused by the fact that the assumption on diffusion limitation is not realistic for the size of rolls. This means that the estimated drip flow actually represents a combination of this diffusion limitation and condensate/drip flow.

The model showed to be able to fit the observed data for the aliphatic GSs glucoraphanin very well, thereby supporting the importance of the mentioned mechanisms. The same was seen for the other aliphatic GSs, however the indolyl GSs were shown to be more heat labile and no increased extractability was observed for this class of GSs.

3.4. Colour

Fig. 4 shows that the greenness level $-a^*/b^*$ increased steadily after blanching followed by steaming for up to 15 min. Subsequently, a steady decrease was observed. Possibly, the increase of greenness level is affected by physical changes in the vegetable matrix, the conversion of non- or less-coloured precursor into more visible green intensity, or a contact between the enzymes and the chlorophyll precursor compounds present in different organelles

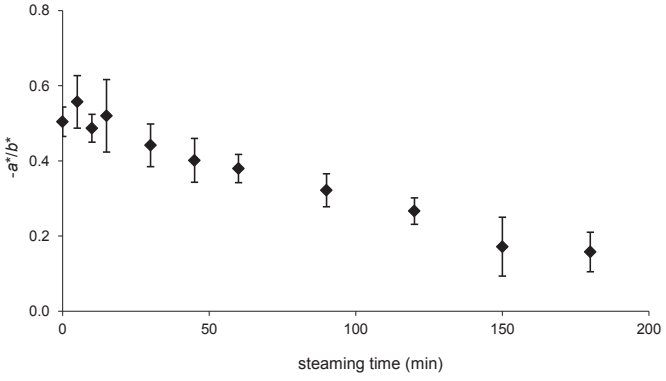

Fig. 4. Greenness level (mean ± SD) of cabbage roll during steaming ($n = 18$).

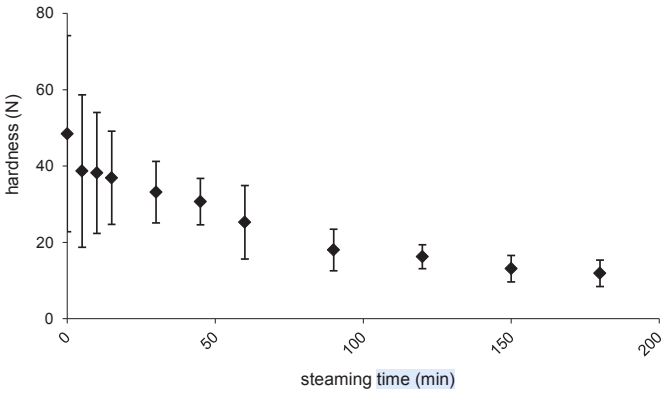

Fig. 5. Hardness (mean ± SD) of cabbage roll during steaming ($n = 18$).

(Tijskens et al., 2001).

The high temperature during prolonged steaming of cabbage roll causes considerable losses of greenness level. Chlorophylls are susceptible to thermal degradation during processing (Von Elbe & Schwartz, 1996). Moreover, leaching of the liberated colouring compounds could occur (Tijskens et al., 2001).

3.5. Texture

Fig. 5 shows the hardness values of the cabbage roll decreased consistently during steaming. Cooking of vegetables or fruit is known to result in an initial loss of instrumental firmness due to membrane disruption and the associated loss of turgor. Additional softening occurs as a result of an increase in the ease of cell separation (Haard & Chism, 1996). Furthermore, cooking can reduce the strength of cell adhesion in many vegetables and fruit through depolymerisation of pectic polysaccharides (Waldron, Smith, Parr, Ng, & Parker, 1997).

The percentage of softening of blanched sample with respect to the raw increased from 20% into 75% at 5 and 180 min, respectively. Previous studies also reported that the degree of softening due to heat treatment is varied depending on the types of both preparation and *Brassica* vegetable (D'Antuono et al., 2007; Miglio et al., 2008).

4. Conclusion

The behaviour of glucosinolates (GSs) of white cabbage during long-term steaming has been studied. The total GSs increase after blanching for 3 min followed by steaming for 10 min. After this initial phase, a decline of total GSs is observed during the long term steaming up to 180 min. This behaviour is attributed mainly to the aliphatic GSs. The indole GSs tend to decrease during the whole process of steaming. Glucoraphanin and glucobrassicin are the two dominant GSs found in the cabbage. In the present study, the mathematical model for glucoraphanin in the cabbage rolls fits the observed concentration profile during steaming, implying that the mathematical model can be used to predict the changes of GS content and the underlying mechanisms are well defined to formulate the model. However, further optimisation on the conditions of steaming to achieve the highest possible GS content in the product should be performed, e.g., by studying the effects of the size of the cabbage roll and the ratio of the water, steam, and rolls, on the retention of GS content and myrosinase activity. The greenness colour of cabbage roll slightly increases during the initial phase of steaming followed by a decrease onwards. The hardness value shows a continuous decline during long term steaming. This

study shows that steaming up to 10 min could promote the health properties and the pattern of changes is correlated with changes of the colour and texture attributes. The acceptable quality in the sense of GS content, colour, and texture can be maintained for up to about 45 min of steaming. The study indicates that long term steaming as is done in food service in Indonesia causes considerable loss of GSs as well as the colour and texture attributes of cabbage roll. Alternative preparation/storage conditions of these products can improve these quality attributes.

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