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The Effect of Thermal Processing on Sensory Properties, Texture Attributes and Pectic Changes in Broccoli

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Abstract

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Broccoli cooked in a convection steam oven at different temperatures and times was evaluated and compared with broccoli boiled in water. Broccoli was subjected to a sensory analysis, and its texture parameters were determined instrumentally. The effect of various thermal processing methods on pectic compounds was analysed. The application of different cooking methods led to significant variations in the analysed attributes. The majority of the observed differences were statistically significant ($P < 0.05$). Broccoli cooked in a convection steam oven at 125°C with 90% steam saturation for 8 min was characterised by the most desirable sensory attributes and scored 8.5 on a 10-cm unstructured line scale. The same samples had the greatest firmness and the highest protopectin content (72.9%). Broccoli boiled in water scored the lowest number of points, and it had the lowest protopectin content (51%).

Keywords: cruciferous vegetables; thermal treatment; organoleptic properties; physical properties; fibre; pectins

Broccoli (*Brassica oleracea* var. *italica*) has been enjoying growing popularity in recent years due to its attractive sensory attributes and high nutritional value (Hrnčiřik & Velišek 2001; Mandelowá & Totušek 2006; Borowski *et al.* 2008; Garitta *et al.* 2013). Research has demonstrated that consumers have a preference for brightly coloured varieties of broccoli with a lower content of bitter tasting glucosinolates (alkenyl and indole glucosinolates) and higher sucrose content (Schonhof *et al.* 2004; Brückner *et al.* 2005). Buttery *et al.* (1976) concluded that dimethyl trisulphide was an important aroma compound in cooked broccoli. The quality of cooked broccoli is affected by genetic factors as well as by the thermal processing method (Wu & Chang 1990; Vallejo *et al.* 2002; Borowski *et al.* 2005; Lin & Chang 2005), who included the applied equipment and cooking parameters such as temperature, time and moisture content.

Thermal processing induces changes in structure-forming components, such as fibre and pectic compounds, nutrients, including proteins and vitamins, and non-nutritive bioactive components, such as glucosinolates and polyphenols. Products cooked with the involvement of various methods differ in their sensory attributes, including firmness, hardness, taste, aroma, and colour, as well as nutritional value (Murcia *et al.* 2000; Vallejo *et al.* 2002; Zia-ur-Rechman *et al.* 2003; Zhang & Hamauzu 2004; Borowski *et al.* 2005; Brückner *et al.* 2005; Lin & Chang 2005; Gliszczyńska-Świgło *et al.* 2006). Heat loosens the structure of broccoli due to changes in the content of pectins which are found mainly in the cell wall and middle lamella. The key changes include deesterification and the subsequent formation of calcium bridges between free carboxyl groups of adjacent pectin molecules (Wu & Chang 1990; Lin & Chang 2005; Sila *et al.* 2009; Van Buggenhout *et al.* 2009; Christiaens *et al.* 2012). Changes in the texture of thermally processed broccoli resulting from variations in the content of pectin fractions have been weakly investigated.

When broccoli is cooked in water, a substantial part of soluble components is transferred to water, which reduces the palatability of the cooked product

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(Petersen 1993; Borowski *et al.* 2005). Alternative cooking methods are recommended for broccoli (Price *et al.* 1998; Murcia *et al.* 2000; Roy *et al.* 2009; Yuan *et al.* 2009). In the catering industry, vegetables are increasingly often thermally processed in convection steam ovens and microwave ovens.

In this study, broccoli cooked in a convection steam oven at different temperatures and times was evaluated and compared with broccoli boiled in water. Broccoli was subjected to a sensory analysis, and its texture parameters were determined instrumentally. The effect of various thermal processing methods on the content of pectic compounds was analysed.

MATERIAL AND METHODS

Sample preparation. The experimental material was a late variety of broccoli (*Brassica oleracea* L.), Volta F1, purchased in a retail chain store in Olsztyn in 2012. Fifteen broccoli heads were used per experimental replication. The average weight of a broccoli head was 550 g. Broccoli was cleaned and separated into florets with stems to produce 5 samples which were cooked in the BECK FCV4EDS convection steam oven (BECK GmbH, Jagsthausen, Germany) with different thermal processing parameters (variants 1–4) and in water (variant 5). The following thermal processing parameters were applied:
1 – steam, 103°C/15 min; 2 – steam, 90°C/30 min; 3 – steam, 125°C/12 min; 4 – combination of hot air (125°C) with 90% steam saturation/8 min; 5 – boiling water, 100°C/7 min (water : broccoli weight ratio – 5 : 1).

Cooked samples (1–5) for chemical analyses were cooled to room temperature (20 ± 2°C) and ground in the Thermomix 31-1 processor (Vorwerk, France).

For sensory evaluation were used whole broccoli samples without cutting to florets and stems like in the case of preparing samples for instrumental texture analysis. Sensory evaluations and instrumental analyses were carried out immediately after sample cooling to 22 ± 2°C. Samples for chemical analyses were freeze-stored at –18°C. Chemical analyses were performed within 4 weeks from sample preparation. The experiment was carried out in three replications.

Chemicals. Anhydrous ethyl alcohol, concentrated sulphuric acid, ammonium oxalate, oxalic acid, sodium tetraborate decahydrate, sodium hydroxide were purchased from PPH POCH (Gliwice, Poland). Galacturonic acid and *m*-hydroxydiphenyl were obtained from Sigma-Aldrich (St. Louis, USA).

Sensory evaluation. The sensory attributes of cooked broccoli were evaluated according to the Polish standard PN-ISO 4121:1998 (Sensory analysis. Methodology. Evaluation of food products by methods using scales) on a 10-cm unstructured line scale. Five sensory attributes were evaluated: aroma intensity, green colour intensity, consistency, bitter taste intensity, and overall quality. The anchors were: none to strong (aroma intensity, green colour intensity and bitter taste intensity), too soft to firm (consistency), bad to very good (overall quality). The assessors were asked to put a cross on 10-cm unstructured line scales for each attribute of all the samples. The length from the start of the line to marked cross was measured with scale and converted to numerical scores for statistical analysis. The assessment was performed by 10 panellists trained in basic sensory evaluation methods and tested for individual sensitivity to sensory stimuli.

Instrumental evaluation of texture attributes. Instrumental measurements of broccoli texture were performed using the Instron 4301 universal testing machine (Instron, Canton, USA) equipped with an interchangeable load cell (model 2518-807, range of forces from 0 N to 100 N) and coupled with a computer for data acquisition and storage (Instron Series IX Automated Materials Tester Version software, v. 8.34.00). A shear test was performed with a single-blade shear cell (Warner-Bratzler Shear, type 2830-013), and the speed of the working element was set at 50 mm/min (Bourne 2002). Broccoli samples were cut in two points perpendicularly to their cross-section – at the distance of 1.5 cm (floret) and 3.5 cm (stem) from the top of the floret. The cross-sectional area (mm^2) was measured at the cutting point in each sample. The resulting force-deformation shear curves were used to determine the following parameters:

F_{1max} – maximum force required to cut the sample (N),
d_{max} – maximum displacement of the cutting element corresponding to F_{1max} (mm),
F_{2max} – maximum cutting force per unit area (quotient of F_{1max} and the cross-sectional area of the cut sample) (N/mm^2),
Z_s – structural firmness of the analysed sample (quotient of F_{1max} and d_{max}) (N/mm),
E_c – total energy required to cut the sample (J).

Twenty measurements (for florets and stems) were performed for each thermal processing variant in each of the three replications.

Determination of total pectin content and pectin fractions. Preparation of the total pectin extract, the

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extracts of water-soluble pectin fractions and extracts of pectin fractions soluble in an aqueous solution of oxalate as well as colorimetric assay were determined by the method proposed by Yu *et al.* (1996). Ground broccoli samples of 3 g were extracted with 25 ml of hot anhydrous alcohol in a boiling water bath for 10 minutes. After cooling, the liquid was separated from the precipitate in the Eppendorf AG laboratory centrifuge (Hamburg, Germany) at 10 000 rpm for 10 minutes. The extraction process was repeated three times. The precipitate was dried at 35°C to constant weight (AIS – Alcohol Insoluble Solids). It was analysed to determine the total pectin content, the content of water-soluble pectin fractions and pectin fractions soluble in an aqueous solution of oxalate. The protopectin content was determined as the difference between the total pectin content and the total content of water-soluble pectins and pectin fractions soluble in an aqueous solution of ammonium oxalate.

Preparation of total pectin extract. Five mg of AIS was combined with 2 ml of concentrated sulphuric acid, the mixture was stirred, and then 0.5 ml of distilled water was added. After 5 min, 0.5 ml of distilled water was added, and the mixture was stirred for 30 min until AIS was completely dissolved. Samples were filtered through glass wool and filled up with distilled water to 25 ml.

Preparation of extracts of water-soluble pectin fractions. A centrifuge tube was filled with 80 mg of AIS and 20 ml of distilled water were added, the mixture was stirred for 1 min, and the supernatant was separated from the precipitate in the Eppendorf AG laboratory centrifuge (Hamburg, Germany) at 10 000 rpm for 10 minutes. The supernatant was removed, and the precipitate was extracted three times. Supernatants were filled up with distilled water to 100 ml.

Preparation of extracts of pectin fractions soluble in an aqueous solution of oxalate. The precipitate was extracted with 20 ml of an aqueous solution containing 0.25% ammonium oxalate and 0.25% oxalic acid. The sample was stirred for 1 min and heated in a boiling water bath. The supernatant was separated from the precipitate in the Eppendorf AG laboratory centrifuge (Hamburg, Germany) at 10 000 rpm for 10 minutes. The supernatant was removed, and the precipitate was extracted three times. Supernatants were filled up with distilled water to 100 ml.

Colorimetric assay. Pectin extract (1 ml) was added to 6 ml 0.0125 M sodium tetraborate decahydrate in concentrated sulphuric acid. The mixture was heated in a boiling water bath for 5 min, and it was cooled immediately. After that, 0.1 ml of 0.15% *m*-hydroxydiphenyl solution in anhydrous ethyl alcohol was added, and left for 15 min for colour development. Absorbance was measured in the Optizen Pop UV/VIS spectrophotometer (Mecasys Co., Ltd., Daejeon, Korea) at 520 nm wavelength against a blank sample where the pectin extract was replaced with distilled water, and 0.15% alcohol solution of *m*-hydroxydiphenyl was replaced with 0.5% aqueous solution of NaOH.

The results were expressed as the equivalent of galacturonic acid based on the standard curve. The total pectin content and the content of different pectin fractions were given in g per 100 g of sample.

Statistical analysis. The experiment was carried out in three replications. The results of chemical analyses were presented in tabular form as the mean values from 9 measurements (n = 9). The results were verified statistically by one-way analysis of variance. The significance of differences between mean values was estimated by Tukey's test ($P < 0.05$). The coefficient of linear correlation (r) between sensory consistency and parameters F_{1max}, F_{2max}, Z_s was calculated. Statistical analysis was performed using the Statistica v. 8.0 software (Statsoft Inc., Tulsa, USA).

RESULTS AND DISCUSSION

Sensory evaluation. The results of the sensory evaluation of broccoli samples cooked under different thermal processing conditions (variants 1–5) are presented in Table 1. The analysed samples differed in green colour intensity, aroma intensity, bitter taste intensity and hardness. Broccoli cooked in a convention steam oven in variant 4 (combination of hot air with a temperature of 125°C and 90% steam saturation, 8 min) received the highest score (8.5) for the overall quality.

It was characterised by the most desirable colour (8.6), firm structure and better consistency (5.5) than the remaining samples. The bitter taste was weakly perceptible in variant 4 (Table 1). The above indicates that under the processing conditions applied in variant 4, the majority of volatile compounds responsible for the bitter taste and pungent aroma of broccoli were removed with steam (Baik *et al.* 2003; Schonhof *et al.* 2004). Samples cooked in a convection steam oven in variants 2 and 3 received the lowest notes in a general evaluation (2.3 and 3.4, respectively). Fenwick and Heaney (1983) as well as Lewis and Fenwick (1987) reported that the typical *Brassica* flavour in broccoli is largely due to

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Table 1. Sensory quality of cooked broccoli (scale 0–10)

Variant	Aroma	Green colour intensity	Consistency	Bitter taste intensity	Overall quality
1	8.7 ± 0.2[a]	5.3 ± 0.3[c]	2.8 ± 0.2[d]	5.4 ± 0.2[c]	5.7 ± 0.4[c]
2	8.0 ± 0.3[b]	2.8 ± 0.2[e]	3.5 ± 0.2[c]	6.5 ± 0.4[b]	2.3 ± 0.2[e]
3	5.2 ± 0.3[c]	4.2 ± 0.1[d]	4.2 ± 0.3[b]	7.1 ± 0.3[a]	3.4 ± 0.1[d]
4	8.1 ± 0.2[b]	8.6 ± 0.3[a]	5.5 ± 0.4[a]	3.3 ± 0.3[e]	8.5 ± 0.4[a]
5	8.7 ± 0.3[a]	8.1 ± 0.2[b]	2.1 ± 0.2[e]	4.5 ± 0.2[d]	6.5 ± 0.3[b]

1 – steam, 103°C/15 min; 2 – steam, 90°C/30 min; 3 – steam, 125°C/12 min; 4 – combination of hot air 125°C with 90% steam saturation/8 min; 5 – boiling water, 100°C/7 min; mean values ± standard deviation in a column marked with the same letter are not significantly different ($P < 0.05$)

glucosinolate-derived volatile isothiocyanates and cyanides released from sinigrin, glucoiberin, and glucoraphanin. Schonhof *et al.* (2004) demonstrated a multiple correlation between bitter taste and the content of sinigrin, gluconapin, progoitrin, glucobrassicin, and neoglucobrassicin with significant $R^2_{multiple} = 0.89$ ($P = 0.01$) in experiments investigating both cauliflower and broccoli. The above authors also noted that the intensity of bitter taste in the analysed vegetables differed across varieties. According to Brückner *et al.* (2005), the majority of consumers have a preference for sweet tasting broccoli, whereas bitter taste and pungent aroma are the least desirable sensory attributes. Yuan *et al.* (2009) observed that steaming is most effective in preserving green colour intensity and minimising chlorophyll loss in comparison with other cooking methods, including boiling, microwaving, stir-frying, and stir-frying/boiling. Our results and the findings of Ślaska-Grzywna (2007) suggest that the sensory properties of broccoli cooked in a convention steam oven are conditioned by temperature, cooking time, and moisture content. According to Petersen (1993), steamed broccoli is generally much more acceptable to consumers than broccoli boiled in water.

Significant variations in the colour, aroma, and texture of broccoli cooked with the use of different methods were observed by Schnepf and Driskell (1994). The same authors noted that an optimal thermal processing method was difficult to choose. In the work of Brewer *et al.* (1995), comparable changes in colour, texture, and vitamin C retention levels were noted in microwaved and steamed broccoli.

Texture attributes. An instrumental analysis revealed that the texture attributes of broccoli were determined by the applied cooking method, and they validated the results of the sensory evaluation. Significant differences in firmness (Z_s), F_{1max}, F_{2max},

Table 2. Selected texture attributes of broccoli florets and stem

Variant	F^*_{1max} (N)	d^*_{max} (mm)	F^*_{2max} (N/mm^2)	Z^*_s (N/mm)	E^*_c (× 10^{-2} J)
Broccoli florets					
1	16.5 ± 4.2[b]	22.1 ± 2.4[b]	0.06 ± 0.02[b]	0.8 ± 0.16[b]	11.0 ± 2.8[bc]
2	17.1 ± 5.4[b]	27.0 ± 5.2[a]	0.06 ± 0.01[b]	0.6 ± 0.11[bc]	16.1 ± 8.4[b]
3	10.5 ± 2.3[bc]	24.5 ± 4.2[ab]	0.06 ± 0.01[b]	0.4 ± 0.04[cd]	9.1 ± 3.4[bc]
4	38.4 ± 6.5[a]	27.8 ± 3.4[a]	0.12 ± 0.03[a]	1.4 ± 0.35[a]	25.3 ± 9.4[a]
5	5.3 ± 2.3[c]	23.4 ± 3.8[ab]	0.04 ± 0.02[b]	0.2 ± 0.06[d]	6.3 ± 2.5[c]
Broccoli stem					
1	9.9 ± 3.3[b]	6.7 ± 0.9[a]	0.5 ± 0.1[c]	1.5 ± 0.5[b]	11.9 ± 4.2[b]
2	16.5 ± 7.1[b]	9.5 ± 4.5[a]	1.2 ± 0.1[b]	1.8 ± 0.5[b]	14.7 ± 5.7[b]
3	12.2 ± 4.9[b]	8.7 ± 3.7[a]	0.9 ± 0.1[b]	1.5 ± 0.4[b]	13.0 ± 5.8[b]
4	35.0 ± 9.5[a]	7.8 ± 1.7[a]	2.7 ± 0.2[a]	4.5 ± 1.2[a]	30.7 ± 7.3[a]
5	14.6 ± 4.5[b]	7.8 ± 3.3[a]	1.0 ± 0.2[b]	1.4 ± 0.6[b]	15.9 ± 5.6[b]

*symbols as in Material and Methods; 1 – steam, 103°C/15 min; 2 – steam, 90°C/30 min; 3 – steam, 125°C/12 min; 4 – combination of hot air 125°C with 90% steam saturation/8 min; 5 – boiling water, 100°C/7 min; mean values ± standard deviation in a column marked with the same letter are not significantly different ($P < 0.05$)

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Table 3. Linear correlation coefficients matrix between evaluated parameters

Evaluated parameters	F^*_{1max}	F^*_{2max}	Z^*_s
Sensory consistency	0.90**	0.93**	0.90**

*symbols as in Material and Methods; **significant at $P < 0.05$

and E_c ($P < 0.05$) were observed in the majority of experimental variants (Table 2). The most highly sensory evaluated samples in variant 4 were characterised by the greatest firmness which was determined at 1.4 N/mm for florets and was threefold higher in stems at 4.5 N/mm. The above samples had the greatest cutting force (38.4 N – florets, 35.0 N – stems) and the highest total cutting energy (25.3 × 10^{-2} J and 30.7 × 10^{-2} J, respectively). Broccoli boiled in water (variant 5) had the lowest firmness (florets – 0.2 N/mm, stems – 1.4 N/mm). The same trend was observed in parameter F_{2max}, i.e. maximum cutting force per unit area. The lowest differences between the analysed samples, both florets and stems, were reported for displacement d_{max} (Table 2).

The findings of other authors (Wu & Chang 1990; Lin & Chang 2005; Ślaska-Grzywna 2007) also indicate that the texture attributes of broccoli are significantly influenced by cooking methods characterised by different temperatures, cooking time, and moisture content, including boiling, steaming, microwaving, stir-frying, and stir-frying/boiling.

In this experiment, significant correlations were observed between sensory consistency and instrumentally determined parameters F_{1max}, F_{2max}, and Z_s with linear correlation coefficients of 0.90, 0.93, and 0.90, respectively (Table 3).

Changes in pectin content. The total pectin content and pectin fraction content – protopectins, water-soluble pectins, and pectins soluble in an aqueous solution of oxalate – were determined in broccoli cooked with the involvement of various methods. Differences were noted in the total pectin content and the content of various pectin fractions (Table 4). Most of the observed differences were statistically significant ($P < 0.05$). The total pectin content ranged from 1.98 g/100 g of water-boiled broccoli (variant 5) to 3.07 g/100 g of broccoli cooked in a convention steam oven (variant 2).

Protopectins were the predominant fraction in all variants regardless of the applied thermal processing method. Broccoli boiled in water had the lowest levels of total pectin content, protopectins and water-soluble pectin fractions. The results can be attributed to the migration of the analysed compounds into boiling water and lower dry matter content of broccoli boiled in water (Borowski *et al.* 2005). The cooking loss of samples processed in a convention steam oven was generally low, and it increased dry matter content by 1–2%. The results are consistent with Petersen (1993). Significant differences in the content of various pectin fractions in cooked broccoli were reported by Wu and Chang (1990), Ni *et al.* (2005), and Christiaens *et al.* (2012). The key changes during thermal processing included de-esterification and the subsequent formation of calcium bridges between free carboxyl groups of adjacent pectin molecules (Chang & Chang 1992). According to Wu and Chang (1990), broccoli cooked at 50, 60, and 70°C had a reduced content of the cold-water soluble pectin fraction and a higher content of pectin fractions soluble in sodium hexametaphosphate and hot water in comparison with raw broccoli. The high-temperature treatment applied in this study leads mainly to chemical de-esterification. Pectin methylesterase may be active during the initial heating phase, but it is degraded in successive phases of thermal processing. According to Sila *et al.* (2009), the increase in

Table 4. Total pectin content and the content of pectin fractions in broccoli samples (g/100 g fresh mass)

Variant	Total pectin	Water soluble pectin	Oxalate soluble pectin	Protopectin
1	2.98 ± 0.04[ab]	0.50 ± 0.03[b]	0.46 ± 0.02[bc]	2.02 ± 0.03[ab]
2	3.07 ± 0.03[a]	0.61 ± 0.02[a]	0.48 ± 0.01[bc]	1.98 ± 0.04[b]
3	2.90 ± 0.04[b]	0.54 ± 0.01[ab]	0.53 ± 0.01[b]	1.83 ± 0.01[c]
4	2.88 ± 0.01[b]	0.33 ± 0.01[c]	0.45 ± 0.02[c]	2.10 ± 0.03[a]
5	1.98 ± 0.03[c]	0.27 ± 0.02[c]	0.70 ± 0.03[a]	1.01 ± 0.02[d]

1 – steam, 103°C/15 min; 2 – steam, 90°C/30 min; 3 – steam, 125°C/12 min; 4 – combination of hot air 125°C with 90% steam saturation/8 min; 5 – boiling water, 100°C/7 min; mean values ± standard deviation in a column marked with the same letter are not significantly different ($P < 0.05$)

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the content of water-soluble fractions during thermal processing may be attributed to thermosolubilisation and/or β-eliminative depolymerisation of pectin at high temperatures (> 80°C).

CONCLUSIONS

In the present study, broccoli cooked with the application of various thermal processing methods differed significantly in its sensory properties, texture attributes and pectin content. Generally, broccoli cooked in a convection steam oven had more desirable taste, aroma, colour and firmness than broccoli boiled in water. The optimal sensory attributes were reported in variant 4 where broccoli was cooked at 125°C with 90% steam saturation for 8 minutes. The resulting florets and stems had the greatest firmness which was determined instrumentally in the Instron universal testing machine. The above samples required the greatest cutting force and the highest total cutting energy. Also, the sample (4) had the highest protopectin content. The results of this study not only expand our knowledge, but also offer practical benefits and can serve as guidelines for vegetable processing and catering companies.

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