Temperature and light conditions at different latitudes affect sensory quality of broccoli florets (*Brassica oleracea L. var. italica*)

Running title: Latitudinal growth conditions affect sensory quality of broccoli florets

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Abstract

BACKGROUND: Broccoli (*Brassica oleracea* L. var. *italica*) is a popular vegetable grown at a wide range of latitudes. Plants were grown in 2009-2011 in pots with standardized soil, irrigation and nutrient supply at natural temperature and light conditions at four locations (42-70 °N). A descriptive sensory analysis of broccoli florets was performed by a trained panel to examine any differences along the latitudinal gradient for 30 attributes within appearance, odour, taste/flavour and texture.

RESULTS: Average results over three summer seasons in Germany, Southern Norway and Northern Norway showed that the northernmost location with low temperatures and long days had highest scores for bud coarseness and uniform colour, while broccoli from the German location, with high temperatures and shorter days, had highest intensity of colour hue, whiteness, bitter taste, cabbage flavour, stale flavour and watery flavour. Results from two autumn seasons at the fourth location (42 °N, Spain), with low temperatures and short days, tended toward results from the two northernmost locations with exception for most texture attributes.

CONCLUSION: Results clearly demonstrate that temperature and light conditions related to latitude and season affect the sensory quality of broccoli florets. Results may be used in marketing special quality regional or seasonal products.

Key words: *Brassica oleracea* L. var. *italica;* climate; latitudes; pre-harvest; semi-field, sensory quality

INTRODUCTION

Vegetable quality is important for consumers, and their perception of quality is often based on sensory characteristics. [1,2] Within the *Brassica* vegetables, broccoli (*Brassica oleracea* L. var. *italica*) is an economic important vegetable known for its high content of health-promoting compounds. [3] It is widely cultivated in many parts of the world over a wide range of temperatures and light conditions related to latitude and season. Different cultivars have a temperature optimum for inflorescence development between 15 and 20 °C, which may affect developmental time [4-6], and there is a risk of abnormal inflorescence when temperatures exceed 30 °C. [7] Photoperiod on the other hand seem to have a limited influence on inflorescence development in broccoli. [6]

In Scandinavia, broccoli is grown even at high latitudes above the Arctic Circle (66 °N). In the summer season, high northern latitudes are associated with long day lengths (up to 24 h) and low mean temperatures (10-12 °C). There is also a difference in light intensity and spectral distribution between latitudes, with lower irradiance and longer periods with high proportion of far-red light at high latitudes. [8] In more southern regions of Europe, where summer temperatures are well above the optimum for broccoli head development, the main production period is normally in autumn or winter, with lower mean temperatures, shorter day lengths and lower irradiation than in summer season. [9]

Growth conditions appear to affect the sensory quality of many vegetables. Hårdh et al. [10] suggest that there are distinct differences in quality between vegetables grown at different latitudes, eg. with higher sugar content and better taste of swedes (rutabaga, *Brassica napus* L. ssp. *rapifera* Metzg.) in northern samples. A recent controlled climate study in swedes, show that several sensory attributes differ along a temperature gradient, with sweet taste, crispiness and juiciness associated with the lowest growth temperature. [11] A similar controlled climate study by Mølmann et al. [12] in broccoli indicates that both temperature and day length may influence several sensory attributes within appearance, flavour and texture. Also in carrots, results from sensory studies suggest that carrots grown at high latitudes taste sweeter than at lower latitudes. [13]

To our knowledge, few attempts have been made to correlate growth and sensory quality of brassicaceous vegetables with temperature and light conditions spanning a wide latitudinal range of locations. Large differences in temperature and light conditions may not only affect the growth cycle, but may also affect sensory attributes within appearance, odour, taste, flavour and texture in a complex manner. Any such effects on sensory quality should preferentially be investigated by descriptive quantitative analysis by an accredited sensory panel.

Therefore, the objectives of the present study are: 1) to investigate developmental times in broccoli between locations with varying temperature and light conditions along a wide latitudinal range in Europe and 2) to investigate the effect of these growth conditions on sensory quality in broccoli florets by using an accredited sensory panel.

EXPERIMENTAL

Plant material and growth conditions

The semi-field setup with broccoli grown in pots were established at four locations spanning latitudes from 42-70 °N in Europe: Pontevedra (42 °N, Spain), Großbeeren (52 °N, Germany), Grimstad (58 °N, Norway) and Tromsø (70 °N, Norway). Soil conditions, fertilization and irrigation were standardized and planting dates in June were synchronized when possible. Seeds, fertilizers and soil were from the same batch for all years and locations. The experiment was carried out over three years (2009 - 2011). In Pontevedra, the summer growth conditions in 2010 – 2011 resulted in abnormal development of heads, and these experiments were therefore repeated in the autumn these two years.

Seasonal growth condition data are summarized in Table 1 and, in addition, detailed daily average temperatures from planting to harvest for all locations are presented in Figure 1. Data for global radiation and standard air temperatures were based on hourly registrations at meteorological stations close to the experimental locations. Day length (photoperiod) was defined as daily duration of global radiation while the period of photosynthetically active radiation (PAR-period) was defined as the period with global radiation above 50 W m^{-2}.

Broccoli seeds cv. Lord were sown in sphagnum peat by the 10^{th} of May at all locations. Four weeks later 20 plants were transplanted to each of 20 large pots filled with 20 L 'Proffjord' soil medium (Grønn Vekst Sør AS, Grimstad, Norway). This is a garden/park compost and sand mixture (1:1 volume) with pH 6.7. The pots had an 8 L underwater system ('Urnekasse', Ø 40 cm, BT Plast AS, Halden, Norway) and were covered with a specially designed silver coloured, umbrella-like lid of polypropylene to protect against rainfall and shade the topsoil to prevent overheating. Ventilation was allowed through a central opening (5 cm) on top of the lid for plant development and a free air space (2-3 cm) between pot and lid.

Before transplanting, 24 g NPK fertilizer (Fullgjødsel® 11-5-18, Yara International), was mixed into the soil of each pot. Additional fertilizer, 8 g of calcium nitrate (Nitrabor, 15.4 % N, Yara International), was added to the water reservoir three and six weeks after planting. The water reservoir was filled up regularly, providing a continuous water supply. The pots were placed in two rows with 10 pots each and were covered with insect net (Figure 2).

Sampling procedures

Harvests were performed when the majority of heads at each location were mature, i.e. in their appropriate developmental stage according to commercial practice. The heads were cut with 5 cm stalks in the morning between 8 and 10 a.m. Minimum 12 heads of optimal maturity were then selected for sensory analysis. From these, florets were cut with 2 cm stalks and weighed. Only those between 10-30 g, or in case of the top central floret, cleaved florets of maximum 30 g per part, were used.

At each location 48 whole and undamaged florets were randomly picked from the selected heads for sensory analyses (maximum 12 assessors, two florets per assessor, 2 sessions). These were divided into four portions of 12 florets and were single steamed on a perforated stainless steel tray in a combi-steamer for four minutes at 100 °C. After steaming, the florets were allowed to cool for 3 minutes at room temperature and then single frozen at -20 °C. Each frozen portion of 12 florets were vacuum-packed in one layer (Figure 2) and stored at -20 °C at each location until they were shipped in dry ice to Nofima (Ås, Norway) for analyses.

Sensory analyses

The sensory analyses were performed by a trained sensory panel at Nofima (Ås, Norway) using a modified quantitative descriptive method (ISO standard 6564:1985E). The panel included 10 (2009) and 11 (2010-2011) professional assessors. Prior to the analysis, a list of attributes with definitions was developed (Supporting information). In total, the panel evaluated 30 attributes within appearance, odour, taste, flavour and texture.

Before analysis, the frozen broccoli florets in vacuum bags were allowed to thaw over night at 4 °C and were then heated in a combi-steamer at 100 °C for 8 minutes. At analysis, the florets were removed from the bags and placed in preheated porcelain cups with lids on a heating plate, until delivery to the assessors. Each assessor was given a sample of two florets from each treatment, one from each of two bags. The samples were tested in a randomized order with respect to treatment, assessor and replicate.

Appearance and odour attributes were evaluated on one of the two florets while flavour and taste attributes were evaluated on the two florets together. Odour was examined by splitting the floret along the stalk, and the area of cutting was smelled. Texture was assessed by biting over the area where the stalk and floret buds met. The intensity of all attributes were graded on a continuous non-structured scale (15 cm) ranged from the lowest intensity (1.0) to the highest intensity (9.0). The data were recorded on a computerized system (CSA, Compusense, Version 4.6, Compusense Inc., Guelph, ON, Canada) which transformed the responses into numbers between 1.0 and 9.0. The final results were obtained by averaging the numbers over assessors and replicates.

Statistical analyses

Analysis of variance (ANOVA: SAS 9.2, SAS Institute, Inc., Cary, NC, USA) was used in the analyses of sensory data. Two different models were used; one for testing average effects over three years (three locations, all summer season) and another with separate analyses each year (four locations, one with different seasons). Factors in the mixed model for testing average effects over years were locations and years (fixed effects) and panelists (random). The errors for testing effects of locations were a linear combination of interactions; MS (location x panelist), MS (year x location x panelist) and MS (error). In the separate analyses for each year the factors were locations (fixed effect) and panelists (random), with the interaction (location x panelist) used as error for testing effects of locations. In analyses with significant differences between locations ($p \leq 0.05$) Tukey′s multiple comparisons test was used at significance level $\alpha = 0.05$.

RESULTS

Development of broccoli heads

The total developmental time for broccoli (planting to harvest) in Tromsø, Grimstad and Großbeeren was quite stable and less than two months in the three summer seasons, except for

Tromsø (2010) with somewhat longer period (Table 1). Summer production in Pontevedra (2009) required about two weeks longer time than at the other locations, and at autumn production (2010-2011) it took more than three months to produce mature heads.

Sensory analyses

Responses over three summer seasons at three locations (52-70 °N)

For results averaged over three years for Tromsø, Grimstad and Großbeeren, 23 out of 30 sensory attributes were significantly different between locations ($p \leq 0.05$, Table 2). For 17 of these attributes the German scores were different from both Norwegian locations. For the two Norwegian locations, however, sensory scores differed significantly only for six attributes.

Between the locations, appearance attributes showed the clearest latitudinal differences, with a north-south gradient for most of them. Broccoli from the northernmost location, Tromsø, distinguished itself with coarser (larger) buds and more uniform colour than at the other locations while broccoli from Großbeeren had the most intense colour hue and whiteness. The differences in odour were less pronounced as only two out of six attributes, acidic odour and green odour, differed significantly. In both cases there were higher intensities in broccoli from the two Norwegian locations as compared to Großbeeren (Table 2).

For taste and flavour attributes, however, differences were clear and broccoli florets from the two Norwegian locations had a more acidic taste and a more pronounced green flavour than from Großbeeren. On the other hand, broccoli from Großbeeren had higher intensity of bitter taste, cabbage flavour, stale flavour and watery flavour than the Norwegian ones. All texture attributes were affected by growth site and again broccoli from the Norwegian locations differed significantly from the German (Table 2). Broccoli from Tromsø and Grimstad were more firm, crispy and juicy and had higher values for toughness and fibrousness than for the Großbeeren location.

For 11 attributes there were a significant interaction between location and year, meaning that results for locations depended on the effect of years (Table 2). In most of these cases there were still significant differences between average results for locations, while for uniformity of bud size, sweet taste and metallic flavour no differences occurred. For sweet taste, the reason for this was opposite ranking of scores in different years, with highest scores for Großbeeren in the first and third year and for Tromsø the second year (see Tables 3-5).

Responses in individual years at four locations (42 -70 °N)

In 2009, broccoli at all locations were produced in the summer season. Most sensory scores this year for appearance, odour, taste and flavour (15 out of 18 attributes with differences between locations), were at similar levels between the two southernmost locations (Pontevedra and Großbeeren, Table 3). And most of them (14 attributes) differed clearly from the northernmost location Tromsø. For the texture attributes; firmness, crispiness, toughness and fibrousness, however, the scores for the Pontevedra broccoli differed clearly from that from Großbeeren, and resembled the results from one or both the Norwegian sites.

In the first trial with autumn production in Pontevedra (2010), most results except for texture attributes, differed clearly from Großbeeren, and resembled the results from summer production in the Norwegian localities. This was the case for 19 out of 22 attributes with significant differences between locations for appearance, odour, taste and flavour (Table 4). For the five texture attributes, however, most results this year for the Pontevedra broccoli differed from both Tromsø and Großbeeren scores, but were closest to the levels for Großbeeren broccoli.

In 2011, only seven out of 25 attributes within appearance, odour, taste and flavour had significantly different scores between locations (Table 5). These were bud coarseness, whiteness, violet colour, sweet taste and green, stale and watery flavour, and all showed similar trends in responses as for the two previous years. The remaining 18 attributes showed no significant differences between locations, in contrast to the previous years with all being significantly different (10 both years, six only in 2010, two only in 2009).

Within texture, however, four out of five attributes in 2011 showed significant differences between locations. The scores for firmness, crispiness and juiciness were similar for Pontevedra and Großbeeren, but differed clearly from both Norwegian locations. For fibrousness, however, only Großbeeren broccoli diverged from Norwegian broccoli.

DISCUSSION

Sensory responses over three summer seasons at three locations (52-70 °N)

Differences between the locations for a majority of sensory attributes clearly demonstrate an influence of different growth conditions on the quality of broccoli florets. Our results, based on a controlled set-up with regard to soil, water supply and fertilization, suggest that latitudinal variations in temperature and light conditions are the main factors affecting these differences.

Some appearance attributes; bud coarseness, colour hue and whiteness, seem to be strongest related to the latitudinal gradients. With decreasing average growth temperatures (19.3 to 11.3 °C) and increasing day lengths (15.5 to 23.6 h) from south to north, there are gradually increasing scores for bud coarseness and colour hue, and likewise gradually decreasing scores for whiteness. For the remaining attributes within odour, taste, flavour and texture, however, results from the two northernmost locations do not deviate much, but both show a clear differences to the southern location (Großberen). This may indicate that climatic conditions outside the range of temperatures and day lengths within Norway are needed to produce major differences for these attributes. The results clearly match findings in a similar semi-field experiment in 2008 at the two Norwegian locations, [12] with highest scores for bud coarseness and colour hue in Tromsø (north) and highest scores for whiteness in Grimstad (south), and minor differences for other attributes.

The broccoli in our studies show a remarkably small variation in growth periods from planting until mature heads at these three strongly different locations with regard to temperatures and light conditions. Our results may suggest that the longer days, with longer photosynthetically active radiation periods at high northern latitudes are able to compensate for temperatures below the optimum for plant development. Another factor is that ambient summer temperatures towards the end of season, seem closer to the optimum temperature for head development [5] in the northernmost than in the southernmost localities. The influence of day lengths on temperature optimums for different developmental responses in broccoli remains to be studied.

Sensory responses in individual years at four locations (42-70 °N)

Results from individual years are presented partly because we were not able to include results from summer production in Pontevedra in the three-season averages. The reason was inadequate head formation during the summers 2010-2011, probably due to too high maximum temperatures or high light intensities, as previously demonstrated by Björkman & Pearson. [7] Also some interactions between locations and years for some attributes, and the inclusion of results from autumn production in Pontevedra, makes it valuable to evaluate the results each year.

Results from 2009, with summer production at all four locations, resembles the north-south three-season trends for the comparison of Tromsø, Grimstad and Großberen, except for the texture attributes. In spite of quite similar temperature and day lengths between Pontevedra and Großberen, all texture attributes but juiciness, differed clearly. Moreover, the Pontevedra results resembled the Norwegian scores which is difficult to explain in light of the contrasting day lengths and temperatures.

In the 2010 season, conditions at autumn production in the southernmost location Pontevedra were quite similar to Tromsø summer conditions regarding temperatures (10-11 °C), while days were shorter (about 11 vs. 23 h). This made it possible to discover any day length effects on sensory attributes. Most results this year from Pontevedra, especially within appearance, taste and flavour were closer to those from Tromsø than from Großbeeren, indicating that temperature rather than light condition may be the main factor determining these attributes. Texture attributes, however, were closer to Großbeeren than to Tromsø, indicating a possible day length response.

The 2011 season differed from the other years by having few, only 11 of 30, attributes with significant differences between locations. This limited number of differences coincides with less contrasting temperatures between the locations this year than the other years. Both Großbeeren and Grimstad had relatively cooler mean temperatures in 2011 vs. the other seasons, while the northernmost location, Tromsø, had its warmest season. In contrast, 27 out of 30 attributes were different between locations in 2010, coinciding with this year having the greatest difference in temperatures between locations. Nevertheless, also in 2011, most texture attributes from Pontevedra broccoli differed clearly from Norwegian broccoli, and showed a close similarity to Großberen results. This supports the above hypothesis of day length being an important factor for development of these attributes at low growth temperatures. However, possible complex interactions between temperatures, day lengths and other factors should be elaborated before final conclusions are made.

In controlled climate and semi-field studies with broccoli, Mølmann et al. [12] stated that day lengths, in addition to temperatures, could be important for some appearance attributes. For bud coarseness they found an interaction between day length and temperature with larger buds at long vs. short days at low temperature (12 °C). This is similar to our results when comparing Pontevedra autumn production with Tromsø conditions (short day vs. long day, both at low temperatures).

Regarding sweet taste, studies of vegetables grown at different latitudes in Scandinavia have previously reported sweeter tasting carrots [13] and “clearly better” tasting swede (rutabaga) at northern locations. [10] For broccoli, a study has showed that low growth temperature produced sweeter taste both at controlled and field conditions. [12] However, in the current study the ranking of sweetness between locations varied strongly between years and no consistent effect of latitudinal conditions could be detected.

Broccoli produced in the warmest season in Großbeeren (2010) and in Pontevedra (summer 2009) had more bitter tasting florets than at the other sites. Bitter taste in Brassicaceae is often linked with high contents of glucosinolates and sometimes flavonols, [14,15] and high sugar contents can reduce this effect. [16] It may therefore be interesting to study the biochemical profile at similar contrasting growth conditions in relation to bitterness, sweetness and other attributes. There are few studies on consumer’s preferences related to sensory quality in broccoli. However, from two studies in broccoli and cauliflower, a high degree of sweetness, juiciness, crispiness and broccoli-like flavour seem to be important for acceptance. On the other hand, intense bitterness, pungency and green/grassy odour or flavor reduced acceptability. [17,18]

The results of the present study are of great relevance as the studied cultivar Lord is widely used across Europe. However, it has repeatedly been shown that *Brassica* cultivars may have varying phytochemical profiles (especially glucosinolates) with potentially different effect on sensory attributes, [17, 19-21] and also varying growth rates related to climate. [6] Therefore, this study on of climatic effects on sensory quality should also be extended with follow up studies on other widely used or emerging cultivars.

CONCLUSIONS

Broccoli can be grown successfully along a large latitudinal range in Europe (42-70 °N), mainly due to a compensation from increasing photosynthetic light periods for decreasing growth temperatures from south to north. Our results demonstrate that these differences in climatic conditions, affect the sensory quality of broccoli florets. Temperature seems to be the most important factor but also temperatures interacting with light conditions play a role, especially for appearance attributes. Low growth temperatures at long days (northern sites) produce coarse buds, acidic taste, crispiness and juiciness, while conditions with high temperatures and shorter days (southern sites) may be associated with bitter taste, cabbage flavour and stale flavour. Low temperature and short day conditions (southern autumn season) show most similarity with northern sites. Results may be used for marketing of broccoli with attractive appearance and good eating quality from optimal growth conditions, regionally or seasonally.

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Table 1. Average temperatures and light conditions from planting to harvest of mature broccoli heads (*Brassica oleracea* L. var. *italica*) at four locations 2009-2011. DAP=days after planting.

	Tromsø 70 °N, 18 °E	Grimstad 58 °N, 8 °E	Großbeeren 52 °N, 13 °E	Pontevedra† 42 °N, 8 °E
2009				
Planting date	9 June	11 June	18 June	11 June
Harvest (DAP)	55	60	56	71
Mean daily photoperiod (h)	23.8	18.2	15.3	15.1
Mean daily radiation (W m^{-2})	204	221	202	247
Mean daily PAR-period (h)	16.4	13.6	13.0	12.8
Mean air temp. (°C)	11.6	16.6	19.0	18.8
2010				
Planting	11 June	11 June	18 June	24 Sept.
Harvest (DAP)	67	59	55	95
Mean daily photoperiod (h)	23.1	18.5	15.7	10.8
Mean daily radiation (W m^{-2})	145	230	233	88
Mean daily PAR-period (h)	14.5	13.7	13.3	7.4
Mean air temp. (°C)	10.4	16.3	20.7	10.8
2011				
Planting	9 June	1 June	16 June	20 Sept.
Harvest (DAP)	54	55	56	91
Mean daily photoperiod (h)	23.8	18.9	15.7	11.1
Mean daily radiation (W m^{-2})	203	203	190	96
Mean daily PAR-period (h)	16.4	13.7	12.6	7.8
Mean air temp. (°C)	11.8	15.8	18.1	13.1
Average 2009-2011				
Harvest (DAP)	59	58	56	-
Mean daily photoperiod (h)	23.6	18.5	15.6	-
Mean daily radiation (W m^{-2})	184	218	208.3	-
Mean daily PAR-period (h)	15.7	13.6	12.9	-
Mean air temp. (°C)	11.3	16.2	19.3	-

†Broccoli from summer production only in 2009 due to incomplete head development in 2010-2011. These years, fields were re-established in autumn.

Table 2. Intensity of sensory attributes in broccoli (*Brassica oleracea* L. var. *italica*) grown in Tromsø, Grimstad and Großbeeren in 2009-2011 summer seasons. Average values of scores 1-9, low to high intensity. n=64 (10-11 panellists × 2 rep × 3 years). P-values (ANOVA) for the main and interactive effects of locations (loc) and years (yr).

2009 - 2011	Tromsø (70 °N)	Grimstad (58 °N)	Großbeeren (52 °N)	p (loc)	p (yr)	p (yr ×loc)
Appearance						
Bud coarseness	6.4 a[†]	5.0 b	3.4 c	<0.001	0.004	<0.001
Uniform bud size	6.0	5.4	5.6	0.106	0.189	0.006
Colour hue	2.7 c	3.6 b	4.3 a	<0.001	0.524	<0.001
Colour intensity	6.4 a	6.1 a	5.4 b	<0.001	0.168	<0.001
Whiteness	2.3 c	3.3 b	4.2 a	<0.001	0.328	0.113
Uniform colour	6.6 a	5.3 b	5.4 b	<0.001	0.304	0.274
Violet colour	1.3 a	1.2 ab	1.1 b	0.006	0.530	0.051
Odour						
Acidic odour	4.0 a	3.9 a	3.3 b	0.002	0.064	0.002
Bitter odour	3.8	3.9	4.0	0.316	0.029	0.159
Green odour	4.2 a	4.0 a	3.5 b	<0.001	<0.001	0.078
Cabbage odour	4.5	4.5	4.9	0.062	0.112	0.338
Metallic odour	3.9	3.8	4.0	0.424	0.207	0.073
Soil odour	2.5	2.4	2.5	0.782	0.136	0.488
Taste/flavour						
Acidic taste	4.3 a	4.1 a	2.9 b	<0.001	0.114	0.584
Sweet taste	4.7	4.6	5.1	0.106	0.064	0.016
Salty taste	1.7 ab	1.7 a	1.5 b	0.013	0.129	0.830
Bitter taste	3.7 b	3.8 b	4.4 a	<0.001	0.014	0.106
Green flavour	4.2 a	3.9 a	3.1 b	<0.001	<0.001	0.495
Cabbage flavour	4.3 b	4.3 b	5.0 a	0.004	0.161	0.720
Metallic flavour	3.7	3.8	4.0	0.060	0.200	0.027
Soil flavour	2.0 b	2.5 ab	2.6 a	0.013	0.049	0.589
Stale flavour	2.3 b	2.3 b	3.8 a	<0.001	0.196	0.018
Watery flavour	2.1 b	2.0 b	3.7 a	<0.001	0.073	0.688
Aftertaste	4.7 b	4.8 ab	5.0 a	0.006	0.367	0.725
Astringency	1.8 b	2.1 a	2.4 a	0.001	0.570	0.014
Texture						
Firmness	3.6 b	4.1 a	1.7 c	<0.001	<0.001	0.026
Crispiness	3.8 a	4.2 a	1.4 b	<0.001	<0.001	0.025
Juiciness	5.8 a	5.6 a	4.7 b	<0.001	0.478	0.256
Toughness	2.3 a	2.6 a	1.4 b	<0.001	0.408	0.065
Fibrousness	2.7 a	3.0 a	1.4 b	<0.001	0.958	0.152

[†]Results for each attribute followed by different letters are significantly different based on Tukey's multiple comparisons test (α=0.05).

Table 3. Intensity of sensory attributes in broccoli (*Brassica oleracea* L. var. *italica*) grown in Tromsø, Grimstad, Großbeeren and Pontevedra in 2009 summer season. Average values of scores 1-9, low to high intensity. n=20 (10 panellists × 2 rep).

2009	Tromsø (70 °N)	Grimstad (58 °N)	Großbeeren (52 °N)	Pontevedra (42 °N)	ANOVA p-value
Appearance					
Bud coarseness	6.3 a[†]	6.3 a	4.2 b	4.3 b	<0.001
Uniform bud size	6.4 a	5.5 ab	5.5 ab	5.0 b	0.005
Colour hue	3.0 b	3.0 b	4.9 a	5.3 a	<0.001
Colour intensity	7.0 a	6.7 a	5.3 b	5.3 b	<0.001
Whiteness	2.7 c	3.2 bc	4.0 a	3.8 ab	<0.001
Uniform colour	7.0 a	5.2 b	5.7 b	5.5 b	<0.001
Violet colour	1.4	1.4	1.1	1.1	0.122
Odour					
Acidic odour	4.5 a	3.8 ab	3.0 c	3.3 bc	<0.001
Bitter odour	3.7	4.2	4.4	4.3	0.167
Green odour	4.8 a	4.4 ab	3.5 b	3.5 b	0.002
Cabbage odour	4.5	4.5	4.9	5.3	0.077
Metallic odour	4.2	4.1	4.1	4.1	0.986
Soil odour	2.2	2.3	2.6	2.9	0.070
Taste/flavour					
Acidic taste	4.7 a	4.4 a	2.9 b	3.2 b	<0.001
Sweet taste	4.7 ab	4.2 b	5.3 a	4.2 b	0.005
Salty taste	1.9 ab	1.9 ab	1.7 b	2.0 a	0.020
Bitter taste	4.1 b	4.3 b	4.5 b	5.5 a	<0.001
Green flavour	4.8 a	4.7 a	3.5 b	3.4 b	<0.001
Cabbage flavour	4.2 b	4.5 b	4.7 ab	5.5 a	0.005
Metallic flavour	3.9	4.1	4.1	4.2	0.567
Soil flavour	1.8 c	2.3 bc	2.8 ab	3.0 a	<0.001
Stale flavour	1.7 b	1.8 b	3.5 a	3.0 a	<0.001
Watery flavour	2.1 b	2.2 b	4.0 a	2.8 ab	0.001
Aftertaste	4.8	4.9	5.2	5.2	0.103
Astringency	1.8 b	2.4 a	2.4 a	2.9 a	<0.001
Texture					
Firmness	3.7 b	4.7 a	1.8 c	4.5 a	<0.001
Crispiness	4.3 ab	5.0 a	1.4 c	3.9 b	<0.001
Juiciness	5.9 a	6.0 a	5.1 b	4.7 b	<0.001
Toughness	2.0 b	3.0 a	1.4 b	3.6 a	<0.001
Fibrousness	2.3 b	3.2 a	1.4 b	3.6 a	<0.001

[†] Results for each attribute followed by different letters are significantly different based on Tukey's multiple comparisons test (α=0.05).

Table 4. Intensity of sensory attributes in broccoli (*Brassica oleracea* L. var. *italica*) grown in Tromsø, Grimstad, Großbeeren (summer seasons) and Pontevedra (autumn season) in 2010. Average values of scores 1-9, low to high intensity. n=22 (11 panellists × 2 rep).

2010	Tromsø (70 °N)	Grimstad (58 °N)	Großbeeren (52 °N)	Pontevedra (42 °N, autumn)	ANOVA p-value
Appearance					
Bud coarseness	7.2 a[†]	5.6 b	2.9 c	3.6 c	<0.001
Uniform bud size	6.2 ab	4.4 c	5.7 b	6.9 a	<0.001
Colour hue	2.5 b	4.0 a	4.5 a	2.2 b	<0.001
Colour intensity	6.5 b	5.8 c	5.3 c	7.2 a	<0.001
Whiteness	1.8 c	3.3 b	4.1 a	2.6 b	<0.001
Uniform colour	7.1 a	5.1 b	5.1 b	7.1 a	<0.001
Violet colour	1.1	1.1	1.0	1.0	0.245
Odour					
Acidic odour	3.7 a	3.8 a	2.9 b	4.1 a	<0.001
Bitter odour	4.4 ab	4.6 ab	4.8 a	4.1 b	0.013
Green odour	3.4 a	3.6 a	2.5 b	3.7 a	0.002
Cabbage odour	4.9 b	4.9 b	5.8 a	4.4 b	0.001
Metallic odour	4.3 ab	3.9 b	4.5 a	3.8 b	0.005
Soil odour	3.1 a	2.7 ab	3.1 a	2.1 b	0.026
Taste/flavour					
Acidic taste	4.0 a	3.9 a	2.4 b	3.9 a	<0.001
Sweet taste	5.7 a	5.1 ab	5.0 ab	4.8 b	0.012
Salty taste	1.4	1.5	1.3	1.6	0.068
Bitter taste	4.0 b	4.2 b	5.2 a	4.0 b	<0.001
Green flavour	3.2 a	3.1 a	2.3 b	3.4 a	0.001
Cabbage flavour	4.8 ab	4.6 b	5.8 a	4.3 b	0.004
Metallic flavour	3.9 b	3.9 b	4.6 a	3.7 b	<0.001
Soil flavour	2.5	3.3	3.0	2.0	0.105
Stale flavour	3.4 ab	2.5 b	4.2 a	2.4 b	<0.001
Watery flavour	2.4 b	2.2 b	4.6 a	2.6 b	<0.001
Aftertaste	5.0 ab	5.0 ab	5.2 a	4.6 b	0.019
Astringency	1.7 b	1.9 b	2.6 a	1.8 b	0.002
Texture					
Firmness	3.2 a	3.4 a	1.4 c	2.0 b	<0.001
Crispiness	3.0 a	3.5 a	1.0 c	1.7 b	<0.001
Juiciness	5.8 a	5.5 ab	4.7 c	4.8 bc	<0.001
Toughness	2.4 a	2.2 a	1.1 c	1.5 b	<0.001
Fibrousness	2.7 a	2.7 a	1.2 b	1.6 b	<0.001

[†] Results for each attribute followed by different letters are significantly different based on Tukey's multiple comparisons test (α=0.05).

Table 5. Intensity of sensory attributes in broccoli (*Brassica oleracea* L. var. *italica*) grown in Tromsø, Grimstad, Großbeeren (summer seasons) and Pontevedra (autumn season) in 2011. Average values of scores 1-9, low to high intensity. n=22 (11 panellists × 2 rep).

2011	Tromsø (70 °N)	Grimstad (58 °N)	Großbeeren (52 °N)	Pontevedra (42 °N, autumn)	ANOVA p-value
Appearance					
Bud coarseness	5.8 a[†]	3.4 c	3.2 c	4.6 b	<0.001
Uniform bud size	5.3	6.2	5.5	5.7	0.065
Colour hue	2.8	3.8	3.6	3.3	0.051
Colour intensity	5.9	6.0	5.6	6.1	0.487
Whiteness	2.4 c	3.6 b	4.4 a	3.3 b	<0.001
Uniform colour	5.9	5.6	5.3	6.1	0.292
Violet colour	1.5 a	1.2 b	1.1 b	1.1 b	0.001
Odour					
Acidic odour	3.8	4.0	3.9	3.2	0.265
Bitter odour	3.3	3.1	3.1	3.5	0.593
Green odour	4.6	4.2	4.4	4.0	0.425
Cabbage odour	4.2	4.0	4.1	4.6	0.382
Metallic odour	3.4	3.5	3.3	3.6	0.599
Soil odour	2.0	2.2	2.0	2.0	0.954
Taste/flavour					
Acidic taste	4.2	4.0	3.4	3.4	0.043
Sweet taste	3.7 b	4.4 ab	5.0 a	5.1 a	0.001
Salty taste	1.7	1.7	1.6	1.6	0.550
Bitter taste	3.2	3.1	3.4	3.1	0.530
Green flavour	4.6 a	4.0 ab	3.5 b	3.5 b	<0.001
Cabbage flavour	3.9	4.0	4.6	4.0	0.089
Metallic flavour	3.4	3.5	3.5	3.3	0.844
Soil flavour	1.6	1.9	2.2	2.3	0.065
Stale flavour	1.7 b	2.7 ab	3.6 a	3.3 a	0.003
Watery flavour	1.7 b	1.7 b	2.6 a	2.1 ab	0.012
Aftertaste	4.3	4.6	4.6	4.5	0.300
Astringency	2.0	2.0	2.1	1.8	0.371
Texture					
Firmness	4.0 a	4.2 a	1.8 b	2.3 b	<0.001
Crispiness	4.1 a	4.2 a	1.7 b	2.0 b	<0.001
Juiciness	5.6 a	5.2 a	4.3 b	4.0 b	<0.001
Toughness	2.5	2.6	1.6	2.6	0.038
Fibrousness	3.1 a	3.0 a	1.6 b	2.5 a	<0.001

[†] Results for each attribute followed by different letters are significantly different based on Tukey's multiple comparisons test (α=0.05).

Figure legends:

Figure 1. Daily average temperatures from planting to harvest of broccoli (*Brassica oleracea* L. var. *italica*) at four locations in 2009-2011. DAP – days after planting.

Figure 2. Semi-field set-up with broccoli (*Brassica oleracea* L. var. *italica*) with two rows of pots (left). Steamed and single frozen florets for sensory analyses were vacuumed and stored at -20 °C (right).