POLISH JOURNAL OF FOOD AND NUTRITION SCIENCES
Pol. J. Food Nutr. Sci. 2005, Vol. 14/55, No 1, pp. 57–62

TEXTURE CHARACTERISTICS OF SELECTED CARROT VARIETIES FOR THE PROCESSING INDUSTRY

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Key words: carrot, industrial varieties, morphological features, texture discriminants

The research was conducted on seven industrial carrot varieties: Bangor, Canada, Carlo, Fayette, Kazan, Kathmandu and Maxima and one lineage – Nun 7375. The carrots were grown under identical agritechnical conditions on an Experimental Farm of the Warsaw Agricultural University in Żelazna near Skierniewice for two consecutive years, 2000 and 2001. The texture of carrot roots was evaluated by means of penetration and compression tests. The penetration and compression curves obtained (in force-shift system) were analysed with the INSTRON IX SERIES Automated Material Testing System ver. 8.04. The significance of difference between the mean values of the texture discriminants examined was determined by analysis of variance (Duncan's test). The calculations were done with STATISTICA^{TM} 6.0. All of the carrot varieties examined varied significantly ($p<0.05$) in the parameters analysed. Only two varieties, *i.e.* Maxima and Kathmandu, were characterised by the most stable texture in two consecutive years of research. The variety Maxima turned out to be the hardest and firmest, whereas the results of measurements obtained for the roots of the variety Kathmandu were opposite. In most cases, weather conditions and agritechnical treatments in particular years of cultivation had a considerable effect on root texture in the varieties examined. The place and method of sampling were also of great importance in terms of the tests applied. The experimental results indicate that both tests are complementary and should be conducted together.

INTRODUCTION

Texture is one of the most important criteria of quality evaluation of food products with the properties of a solid body. It is defined as a set of physical properties, perceptible with the sense of touch, related to deformation, refinement and fluidity of foodstuffs, resulting from the force applied and objectively defined function of force, time and strain [Sadowska, 1983a]. The quality of fruit and vegetables depends, to a high extent, on the firmness of their soft tissues [Gołacki, 1998]. The key determinant of the texture of fruit and vegetables is cell wall. It affects plant tissue in such a way that it undergoes mechanical deformation and damage under the influence of particular factors (Figure 1).

Carrots are valuable raw material in fruit-and-vegetable processing because they are rich in nutrients. However, their roots cause a number of technical problems due to specific morphological structure, high hardness and firmness, compared with other vegetables. It is quite difficult to follow structural changes in the carrot root and its texture because it is composed of morphological parts (phloem and xylem) which differ in microscopic structure [Fornal & Błaszczak, 2001]. The proportion of these morphological parts in the total weight of the root is not a constant value. It depends on carrot variety and growing conditions.

Carrot microstructure is most often described as the structure of a honeycomb [Nielsen *et al.*, 1998]. Regular structure of a honeycomb changes during processing and storage. Sometimes there appear the so-called tracheal elements, *i.e.* sequences of ligneous vessels and tubules located in the xylem, which significantly affect root texture. Only for this reason it is important that the proportion of the central cylinder (xylem) in the root be as low as possible.

Compared with the other vegetables with a high moisture content when fresh, the following properties can be attributed to carrot roots: (1) a high value of the area-to-volume ratio, resulting from elongated shape; (2) very homogenous structure both in transverse and longitudinal section (*i.e.* structure of a honeycomb), which results from the fact that the root is composed mainly of cells of basic tissue (parenchyma); (3) small size of basic tissue cells; (4) low hydraulic conductivity of tissues; (5) high values of moduli of elasticity determined on the basis of both theory of elasticity and viscoelasticity; (6) slight compressibility; (7) high turgor and strong internal stress which causes even spontaneous longitudinal cracking in roots; (8) strong sensitivity to the loss of water [Gołacki, 1998].

The mechanical properties of carrot roots have not been the subject of systematic research so far. The studies were usually a supplement to biochemical examination related to the evaluation of particular varieties or keeping quality of roots. The authors dealing with this issue determined some of their properties such as hardness, resistance to bending, compression and cutting, and searched for a correlation

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with other properties [Gołacki, 1998; Kowalska *et al.*, 2001].

In fruit and vegetables, the processes of compression and shearing have the largest parts in total deformation [Sadowska, 1983b]. Thus, two tests, of penetration and compression, are used most often for the evaluation of raw material quality.

The penetration test involves the measurement of the depth of mandrel penetration under the influence of the force applied after a specified time, or of the time a mandrel needs to achieve a standard depth. A flat-topped mandrel with circular section is recommended for the examination of food of anisotropic structure, fibrous in particular, *e.g.* carrot roots [Sadowska, 1983a].

Compression involves placing a cylinder- or cube-shaped sample between two parallel plates, after which one of them is pressed at constant speed which causes sample compression (parallel plate uniaxial compression test). At the same time the value of the sample compression force is registered as a function of deformation or time [Dobrzycki & Baryłko-Pikielna, 1986; Bourne, 2002].

The use of carrots as raw material in the fruit-and-vegetable processing industry is connected with a number of problems related to their texture and consequently to appropriate root pre-treatment. The industry is more and more interested in objective methods for the analysis of raw material texture, evaluation of their quality and processing value.

Therefore, the aim of the present study was to answer the question: to what extent hardness, structure firmness and compressibility are variety-dependent properties of carrots used for industrial purposes, and how significant differences in these parameters can be determined for selected varieties in the simplest possible way.

MATERIAL AND METHODS

The experimental material included seven industrial carrot varieties: Bangor, Canada, Carlo, Fayette, Kazan, Kathmandu and Maxima, and one lineage – Nun 7375. The carrots were grown under identical agritechnical conditions on an Experimental Farm of the Warsaw Agricultural University in Żelazna near Skierniewice for two consecutive years, 2000 and 2001.

Selected discriminants of root texture for the carrot varieties examined were determined with penetration and compression tests [Sadowska, 1983a,b; Dobrzycki & Baryłko-Pikielna, 1986; Bourne, 2002]. Replaceable working elements (a penetrating mandrel and a compressing anvil) were installed in UMT Instron 4301 with a 0–1000 N measuring head. Speed at which a working element traveled amounted to 50 mm/min in both tests.

Cylindrical samples (10 mm-thick) were cut out from three parts of the carrot root, *i.e.* the base side, the central part and the top, and exposed to a penetration test in the

TABLE 1. Results of the penetration test of the selected industrial varieties of carrot*.

Texture parameter	Sample for test	Variety/ lineage							
		Bangor	Canada	Carlo	Fayette	Kathmandu	Kazan	Maxima	Nun 7375
		Year of investigation – 2000							
$F_{p\,max}$ (N)	base side	67.27^{bce}	49.93^{adefgh}	52.40^{aefh}	60.87^{be}	37.60^{abcdfgh}	69.20^{bceg}	59.40^{bef}	63.67^{bce}
	central part	58.33^{e}	57.73^{ef}	53.40^{defh}	63.67^{ce}	39.33^{abcdfgh}	64.47^{bce}	59.07^{e}	60.60^{ce}
	top	54.73^{cde}	51.53^{defg}	48.80^{adefg}	60.93^{abceh}	41.27^{abcdfgh}	58.07^{bceh}	59.07^{bceh}	51.47^{defg}
	half-cylinder	67.65^{bdgh}	76.20^{acef}	68.05^{bdgh}	76.30^{acef}	65.50^{bdgh}	69.85^{bdh}	73.10^{ace}	77.55^{acef}
d_p (mm)	base side	2.49^{eh}	2.77	2.53^{eh}	2.79	3.95^{acg}	3.10	2.33^{eh}	3.84^{acg}
	central part	3.25^{bg}	2.03^{aefh}	2.44^{fh}	2.61^{h}	3.23^{bg}	3.35^{bcg}	2.33^{aefh}	3.83^{bcdg}
	top	2.35	2.17	1.98	1.97	2.48	1.95	2.33	2.62
	half-cylinder	3.22^{bdg}	2.56^{aef}	2.94^{df}	2.21^{acefh}	3.35^{bdg}	3.54^{bcdgh}	2.62^{aef}	2.88^{df}
Z_p (N/ mm)	base side	30.26^{e}	22.01	26.22	24.16	17.07^{ag}	26.11	30.59^{e}	21.79
	central part	20.02^{bdeg}	28.76^{aceh}	22.43^{be}	26.04^{aeh}	14.47^{abcdfg}	23.44^{e}	26.34^{aeh}	17.95^{bdg}
	top	24.48	25.32	26.19	31.47^{e}	21.81^{df}	31.41^{e}	26.34	25.09
	half-cylinder	22.31^{bdgh}	29.87^{acdef}	23.84^{bdegh}	35.69^{abcefgh}	19.71^{bcdgh}	22.29^{bdgh}	28.00^{acdef}	27.45^{acdef}
		Year of investigation – 2001							
$F_{p\,max}$ (N)	base side	55.47^{eg}	57.20^{eg}	61.33^{ef}	55.33^{eg}	45.60^{abcdfgh}	54.13^{ceg}	64.93^{abdefh}	55.67^{eg}
	central part	53.80^{deg}	56.67^{deg}	56.33^{deg}	48.33^{abcfgh}	45.73^{abcfgh}	58.40^{deg}	73.67^{abcdefh}	56.53^{deg}
	top	52.33^{bcg}	57.07^{adef}	56.87^{adef}	51.53^{bcg}	52.00^{bcg}	50.47^{bcg}	57.73^{adef}	53.87
	half- cylinder	66.85^{bcdefgh}	78.00^{ag}	80.55^{adg}	74.70^{acfg}	76.95^{ag}	81.10^{adg}	86.80^{abcdefh}	78.25^{ag}
d_p (mm)	base side	2.44^{ch}	2.95^{h}	3.76^{a}	3.39	3.31^{h}	3.03^{h}	3.62	4.50^{abef}
	central part	2.71	2.67	3.12	3.08	2.55	2.95	2.41	3.06
	top	2.23^{dg}	2.62	2.12^{dg}	3.18^{aceh}	1.95^{dg}	2.40	3.13^{aceh}	2.05^{dg}
	half-cylinder	2.30^{cdefh}	2.65^{c}	3.22^{abg}	3.02^{ag}	2.86^{a}	2.82^{a}	2.52^{cdh}	2.98^{ag}
Z_p (N/ mm)	base side	25.62^{eh}	22.67	20.88	19.79	16.95^{a}	19.83	19.17	16.40^{a}
	central part	22.19^{g}	23.90^{g}	20.63^{g}	18.03^{g}	20.68^{g}	20.73^{g}	32.18^{abcdefh}	22.92^{g}
	top	26.30	23.56	27.75^{d}	20.12^{ceh}	29.93^{df}	22.72^{eh}	23.60	29.86^{df}
	half-cylinder	30.04^{g}	29.88^{g}	26.71^{g}	27.54^{g}	27.38^{g}	29.40^{g}	34.88^{abcdefh}	26.83^{g}

* means in the rows marked with different letters are significantly different ($p<0.05$)

plane parallel to the axis. Determinations were performed in 15 repetitions (per root) for 15 roots per variety. In a penetration test carried out in the plane perpendicular to the root axis, 40 mm-long half-cylinders were cut out from the central part. Determinations were performed in 20 repetitions for 15 roots per variety.

Mean maximum force achieved during sample penetration to a depth of 7 mm was used as a measure of hardness. The test was conducted with a flat-topped mandrel of circular section and diameter of 4 mm. Structure firmness of the samples examined was determined calculating the ratio of the force applied to the penetration depth (penetration of a mandrel) for both planes, parallel and perpendicular to the root axis.

The compression test was performed on 10×10×10 mm cubes cut out from 15 carrot roots per variety. The test was carried out with a 2830-011 compressing anvil in 12 repetitions. Mean maximum compressive force necessary for 50% deformation of the sample was used as a measure of compressibility of the carrot varieties examined. Structure firmness of the samples was determined calculating the ratio of compressive force to shift corresponding to the above-specified deformation.

The measuring error in both tests amounted to ±1% of the reading value.

The penetration and compression curves obtained (in force-shift system) were analysed with the INSTRON IX SERIES Automated Material Testing System ver. 8.04 program.

The parameters analyzed were: $F_{p\,max}$ – maximum force obtained during the penetration test of the sample examined (N); d_p – shift (penetration depth) corresponding to $F_{p\,max}$; the distance the mandrel travels until the maximum penetration force is achieved (mm); Z_p – firmness of the structure examined; quotient of $F_{p\,max}$ and d_p (N/mm); $F_{c\,max}$ – maximum force necessary to achieve 50% strain in a sample during the compression test (N); d_c – shift corresponding to $F_{c\,max}$; the distance the compression anvil travels until 50% strain in a sample is achieved (mm); Z_c – firmness of the structure examined; quotient of $F_{c\,max}$ and d_c (N/mm).

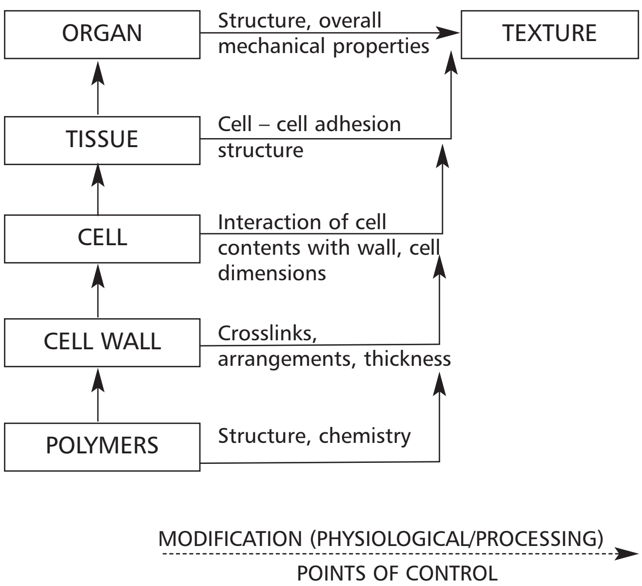

FIGURE 1. Schematic presentation of structural levels which influence mechanical properties of plant tissues [Waldron *et al.*, 1997].

The significance of differences between the mean values of the texture discriminants examined was determined by analysis of variance (Duncan's test). The calculations were done with STATISTICA™ 6.0.

RESULTS AND DISCUSSION

All of the carrot varieties examined differed significantly ($p<0.05$) in the texture discriminants analysed (Table 1 and 2). The research results show that the majority of varieties gathered in 2001 were characterised by higher root hardness than the varieties collected in the year 2000. Weather conditions (temperature, insulation, rainfall) in particular years of carrot cultivation, and some of the agritechnical treatments (*e.g.* irrigation) could have a considerable effect on the formation of carrot root texture.

The results of the penetration test conducted on the varieties from the year 2000 indicate that, irrespective of the plane and place of penetration, the highest hardness (expressed as $F_{p\,max}$) and structure firmness (Z_p) were recorded for varieties Fayette, Maxima and Canada, whereas the lowest – for the variety Kathmandu (Table 1). The results of the test for the varieties from 2001 were slightly different (Table 1). The variety Maxima was characterised by the highest hardness and firmest structure. The lowest values of these two parameters were reported for varieties Kathmandu and Fayette. These results indicate that only two varieties, *i.e.* Maxima and Kathmandu, were characterised by quite stable texture in particular years of research, irrespective of weather conditions and treatments. The variety Maxima turned out to be the hardest and firmest, whereas the results of measurements obtained for the roots of the variety Kathmandu were opposite.

Due to the specific morphological structure of carrot roots, the place and sampling method were of great importance as regards the penetration test (Table 1). The most significant differences among the varieties ($p<0.05$) in the parameters examined were observed when the penetration force was exerted perpendicularly to the root axis. In the case of the penetration force exerted parallel to the axis, the most significant differences ($p<0.05$) were found in the central part of the root.

Sample penetration curves are presented in Figure 2. Their courses are typical of vegetables. These are C-type curves. In this case the force grows rapidly until the yield point (which corresponds to the value of $F_{p\,max}$) is reached. When it is exceeded further deformation of the material

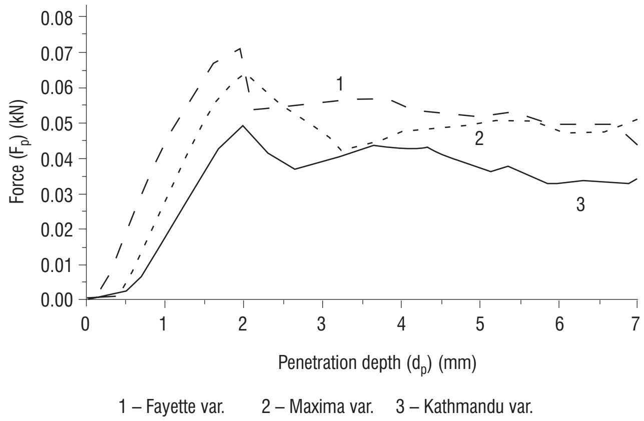

FIGURE 2. Sample penetration curves for the selected industrial carrot varieties in a force-penetration depth system.

TABLE 2. Results of the compression test of the selected industrial varieties of carrot*.

Texture parameter	Variety/ lineage							
	Bangor	Canada	Carlo	Fayette	Kathmandu	Kazan	Maxima	Nun 7375
	Year of investigation – 2000							
$F_{c\,max}$ (N)	235.33^{cdegh}	219.67^{cdeh}	183.08^{abef}	166.42^{abf}	146.83^{abcfg}	239.83^{cdegh}	191.50^{aefh}	152.58^{abfg}
d_c (mm)	3.93^{bdeg}	3.33^{ah}	3.81^{d}	3.23^{ach}	3.42^{ah}	3.49^{h}	3.42^{ah}	4.03^{bdefg}
Z_c (N/mm)	60.86^{ceh}	67.02^{cdegh}	48.68^{abfh}	51.79^{bfh}	43.71^{abfg}	70.04^{cdegh}	56.52^{befh}	38.72^{abcdfg}
	Year of investigation – 2001							
$F_{c\,max}$ (N)	203.25^{bcg}	240.25^{acdegh}	304.75^{abdefh}	177.58^{bcg}	192.25^{bcg}	213.50^{cgh}	274.92^{abdefh}	175.83^{bcfg}
d_c (mm)	3.42	3.41	3.97^{eh}	3.68^{e}	3.06^{cdf}	3.73^{e}	3.64	3.16^{c}
Z_c (N/mm)	60.40^{cg}	71.42^{dh}	77.04^{adfh}	49.78^{bceg}	64.87^{d}	59.22^{cg}	77.28^{adfh}	57.63^{bcg}

* means in the rows marked with different letters are significantly different ($p<0.05$)

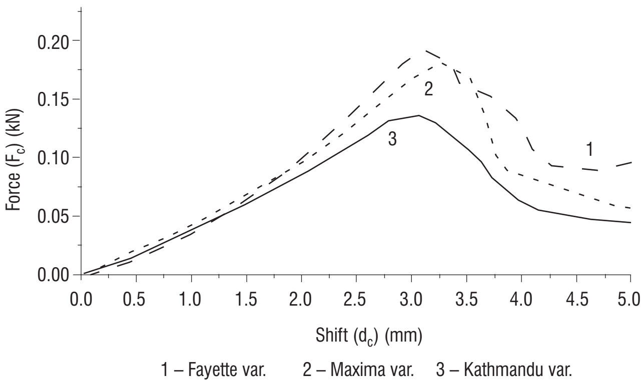

FIGURE 3. Samle compression curves for the selected industrial carrot varieties in a force-shift system.

requires the application of successively weaker forces [Sadowska, 1983a; Bourne, 2002]. The dependence of the puncturing force on the area or circumference of a flat-topped mandrel is of linear nature. The slope of these curves characterises resistance of the material to compression and shearing [Sadowska, 1983b].

After conducting a compression test it was found that among the carrot varieties grown in 2000 Kazan, Canada and Bangor were characterised by the highest resistance to 50% sample degradation and structure firmness, whereas Kathmandu, Nun 7375 lineage and Fayette were characterised by the lowest values of these parameters (Table 2). Slightly different results were obtained in 2001. The highest values of $F_{s\,max}$ and Z_s were noted for varieties Carlo, Maxima and Canada, and the lowest – for Fayette, Nun 7375 lineage and Kathmandu (Table 2). Summing up the results of the compression test for the varieties examined in two consecutive years, it can be stated that the roots of varieties Canada, Kathmandu, Nun 7375 lineage and Fayette were characterized by the most stable texture properties.

Sample compression curves are presented in Figure 3. Their courses are most similar to the so-called B-type curve, where the sample deformation rate is directly proportional to the compressive force applied [Bourne, 2002].

CONCLUSIONS

1. The texture parameters examined are variety-dependent properties of carrots used for industrial purposes; except for varieties Kathmandu and Maxima they were not stable in consecutive years of growing.

2. Highly significant differences ($p<0.05$) in the texture parameters examined for the selected varieties occur when the penetration force is exerted in the plane perpendicular to the root axis, and in the central part of the root when the penetration force is exerted parallel to the axis.

3. The results of both tests prove that they are complementary and when conducted together they allow more accurate characteristics of the texture of industrial carrot varieties.

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Received October 2003. Revision received November 2003 and accepted March 2004.

CHARAKTERYSTYKA TEKSTURY WYBRANYCH ODMIAN MARCHWI PRZEMYSŁOWEJ

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Materiałem do badań było siedem przemysłowych odmian marchwi: Bangor, Canada, Carlo, Fayette, Kazan, Kathmandu i Maxima oraz jeden ród: Nun 7375. Marchew uprawiana była w dwóch kolejnych latach (2000 i 2001) w jednakowych warunkach agrotechnicznych w Gospodarstwie Doświadczalnym SGGW w Żelaznej k. Skierniewic. Do oceny tekstury korzeni marchwi zastosowano testy penetracji oraz ściskania. Uzyskane krzywe penetracji oraz ściskania (w układzie siła-przesunięcie) analizowano korzystając z oprogramowania INSTRON IX SERIES Automated Material Testing System ver.8.04. W celu określenia istotności różnic pomiędzy wartościami średnimi badanych wyróżników tekstury zastosowano metodę analizy wariancji (test Duncana). Obliczenia wykonano korzystając z programu komputerowego STATISTICA^{TM} 6.0. Wszystkie badane odmiany marchwi były istotnie zróżnicowane ($p<0{,}05$) pod względem analizowanych parametrów. Najbardziej stabilną teksturą w dwóch kolejnych latach badań cechowały się jedynie dwie odmiany spośród wszystkich badanych, tj. Maxima i Kathmandu. Odmiana Maxima okazała się najtwardsza i najbardziej zwięzła, odwrotnie było w przypadku odmiany Kathmandu. W większości przypadków w kształtowaniu tekstury badanych korzeni marchwi duże znaczenie mogły mieć warunki klimatyczne i agrotechniczne w poszczególnych latach uprawy. Nie bez znaczenia było również miejsce i sposób pobierania próbek do testów. Uzyskane wyniki badań wskazują na zasadność stosowania obu testów łącznie z uwagi na ich komplementarność.