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THE ACCUMULATION OF CHEMICAL COMPOUNDS IN STORAGE ROOTS BY CARROTS OF DIFFERENT CULTIVARS DURING VEGETATION PERIOD

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Abstract. In 2006–2008 the field experiment was carried out in Warsaw University of Life Sciences to determine the differences in accumulation of some chemical compounds in the storage roots of carrot cultivars of various colour and shape of the root. Carrot cvs.: 'Perfekcja', 'Interceptor', 'Vita Longa', 'Nebula', 'Purple Haze', 'Deep Purple', 'Mello Yello' and 'White Satin' were the objects of the experiment. In intervals of three weeks dry matter, total sugars, total carotenoid and nitrates(V) contents were determined in the roots. Also a relationship between the increase of storage root mass during the plants growth and changes in the content of chemical compounds was investigated. Results showed a significant differentiation between the cultivars in respect of chemical composition of storage roots as well as substantial changes of the composition during the plants growth. The highest sugars, soluble solids and carotenoid contents at the end of vegetation period were found in storage roots of purple-orange coloured cultivar 'Purple Haze'. Strong relationship (determination coefficient R^2 above 80%) between dry matter, sugars and soluble solids accumulation in the storage roots and storage roots mass increase was established. The relationship for carotenoid and nitrates accumulation was much weaker (below 50%). The relationship between dry matter of the roots and sugars or soluble solids accumulation was also strong.

Key words: carrot, cultivars, vegetation period, dry matter, sugars, nitrates, carotenoid compounds

INTRODUCTION

Carrot (*Daucus carota* L.) is one of the most important vegetable crops grown in temperate climate zone. Chemical composition of carrot storage roots relates to a high degree to a genotype and agricultural practices [Nilsson 1987, Brunsgaard et al. 1994, Warman and Havard 1997]. Sugars and carotenoid contents in carrot roots are important

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quality parameters of the product [Mazza 1989]. According to USDA database [Anonymous 2004], raw carrot roots contain on average 12% of dry matter, 4.5% of sugars and 5.7 mg 100 g^{-1} of β-carotene.

Sugars are the main storage compounds in carrot roots, they account for 34–70% of dry weight of the roots and are stored in the vacuoles of the parenchyma [Nilsson 1987]. Sucrose is the predominant storage sugar at roots full maturity, and its content reaches 3.6% f.w. [Daie 1984]. Growing and storage conditions affect the content of sugars in carrots [Lee 1986, Suojala 2000, Seljasen et al. 2001, Gajewski and Dąbrowska 2007].

It is believed that carrot is a good source of carotenoid compounds for humans. Carotenoid compounds found in carrots consist of the larger amount of α-carotene and β-carotene [Simon and Wolff 1987]. Skrede et al. [1997] found that high carotenoid content results in a more reddish and darker colour of the roots. Carotenoid content in carrots increases with the maturation of the roots [Lee 1986, Rosenfeld 1998].

Nitrates in vegetables are of major concern, since vegetables are the main source of these compounds for human population. The Joint FAO/WHO Expert Committee established in 2002 the acceptable daily intake of nitrates at a level of 3.7 mg per kg of body weight per day, equivalent to 222 mg of nitrates per day for adult of 60 kg of body weigh [Santamaria 2005]. In Poland acceptable content of nitrates in carrot roots was established in 2003 at a level of 400 mg NO_3 kg^{-1} f.w. for adults and 200 mg NO_3 kg^{-1} f.w. for children [Anonymous 2003]. Factors affecting nitrates accumulation in plants, including fertilization, environmental conditions and harvest date, are widely investigated [Cserni and Prohaszka 1988, Drlik and Rogl 1992, Mazur 1992, Gutezeit 1999, Gutezeit and Fink 1999, Santamaria 2005, Kona 2006, Gajewski et al. 2009].

The first cultivated carrot types were purple or violet. Yellow and orange types were derived from this anthocyanin type by selection process [Banga 1984]. Most carrot cultivars grown in Europe belong to the orange coloured type, but several cultivars of other root colour – creamy-white, yellow, purple and violet have been bred from Asian lines [Rubatzky et al. 1999]. According to Alasalvar et al. [2005] purple coloured carrots contain higher amount of phenolics, mainly anthocyanins, and show higher antioxidant capacity.

The objective of the study was to determine the relationship between duration of vegetation of carrot cultivars differed in root colour and shape as well as accumulation of some chemical compounds in the storage roots – dry matter, sugars, carotenoids and nitrates. Also a relationship between changes of root mass during plant growth and its chemical composition was investigated.

MATERIAL AND METHODS

The three-year experiment was carried out in Warsaw University of Life Sciences in 2006–2008. Carrots were grown in the experimental field in Warsaw-Wilanów, in an alluvial soil of pH 6.0–6.5, humus content 1.9–2.3% and underground water level 150–200 cm. Fertilizing of the field was applied according to the results of soil analysis. The amount of nutrients in the soil was kept at a level between 180–200 mg K dm^{-3}, 60–80 mg P dm^{-3}, and nitrogen was applied at the rate of 120 kg N ha^{-1}. Half of the

N dose was applied before sowing and the rest in mid-season. Carrot seeds were sown to standard ridges in successive years in the following terms: May 12th, May 15th, May 13th, at the rate of 0.8–1.0 mln seeds per 1 ha. The emerging time of the plants of all cultivars was similar in each year of the study. For weeds control Stomp 330 EC herbicide was applied five days after sowing, in the dose of 4 L ha^{-1}.

Eight carrot cultivars of different storage root colour and shape were used in the study – 'Perfekcja', 'Interceptor' F_1, 'Vita Longa', 'Nebula' F_1, 'Purple Haze' F_1, 'Deep Purple' F_1, 'Mello Yello' F_1, 'White Satin' F_1. Characteristics of the cultivars: 'Perfekcja' – roots orange coloured cylindrical, 'Interceptor' – roots orange-red coloured, elongated; 'Vita Longa' – orange coloured, conical; 'Nebula' – orange coloured, cylindrical; 'Purple Haze' – purple coloured, with orange core; 'Deep Purple' – purple coloured; 'Mello Yello' – yellow coloured; 'White Satin' – creamy-white coloured.

The field experiment with carrot plants of eight cultivars was established in four replicates. The plot area for carrots of one cultivar in one replicate was 10 m^2. Carrot roots were harvested at 3-week intervals during vegetation period, since 7th week after plants emerging (i.e. beginning of June) to 19th week (i.e. mid-October). In each term the roots were picked from the ridge of 2 m length, from each field replicate, to determine biometric traits of the roots, and randomly chosen 20 roots of marketable quality from each field replicate were subjected to chemical analyses. All analyses were done on representative samples of collected plant material.

Dry matter of the roots was determined by drying samples in 105°C, until stable weight. Total sugars were determined by standard Luff-Schoorl's method. Soluble solids were determined with digital refractometer.

Carotenoid content in the roots was determined spectrophotometrically, according to Polish Standard [PN-90/A-75101.12]. Deeply frozen samples of the roots were grounded with anhydrous sodium sulfate and extracted by hexane. Total carotenoid content was determined with the UV-1201V spectrophotometer (Shimadzu, Japan), using the wavelength of 450 nm.

Nitrates (NO_3) content was determined spectrophotometrically. Finely grated roots were extracted with acetic acid (10 g of grated roots + 100 ml of 2% acetic acid + active carbon to eliminate colour). Filtrated extracts were injected to Fiastar device (Tecator, Sweden). Nitrates contents were determined at the wavelength of 440 nm.

Data obtained were statistically evaluated with ANOVA (Statgraphics Plus 4.1 software). For comparison of the content of chemical compounds in the roots of the carrot cultivars in each term of harvest one-way ANOVA was applied. For comparison of the means for the contents of chemical compounds in the roots in different terms one-way ANOVA was applied as well. LSD values were determined with Tukey's HSD test at $P < 0.05\%$. Data presented in the tables are means for three seasons of the study.

RESULTS AND DISCUSSION

Carrot storage roots were characterized by various dry matter content in different terms of vegetation (tab. 1). At the beginning of plants vegetation (7 weeks after emerging) dry matter varied from 7.7 to 11.3%, depending on the cultivar, and at the end of vegetation increased to 8.7–13.9%. On average, dry matter reached 9.7% at the beginning of vegetation and 11.5% in the term of roots full maturity. The lowest dry matter content showed roots of the creamy-white coloured cultivar 'White Satin' (8.7%), and the highest of the purple-orange coloured 'Purple Haze' (13.9%). During carrots growth, dry matter content increased nearly linearly, and the biggest differences between the cultivars in respect of dry matter content were observed in the last term of harvest.

Table 1. Dry matter (% f.w.) in carrot roots during vegetation period in relation to the cultivars (means of 2006–2008)
Tabela 1. Sucha masa (% św.m.) korzeni marchwi w okresie wegetacji w zależności od odmiany (średnie z lat 2006–2008)

Cultivar Odmiana	Period from emerging – Okres od wschodów					Means Średnie
	7 weeks 7 tygodni	10 weeks 10 tygodni	13 weeks 13 tygodni	16 weeks 16 tygodni	19 weeks 19 tygodni	
Perfekcja	11.06	11.47	11.70	12.52	13.15	11.98
Interceptor	10.23	10.82	10.80	11.00	11.23	10.82
Vita Longa	9.46	9.69	9.83	10.01	10.66	9.93
Nebula	9.27	10.12	10.48	11.07	11.55	10.50
Deep Purple	9.63	10.51	11.34	11.72	12.37	11.11
Purple Haze	11.34	11.85	12.54	13.03	13.86	12.52
Mello Yello	8.55	8.75	9.19	9.45	10.16	9.22
White Satin	7.75	8.20	8.58	8.70	8.74	8.39
Means – Średnia	9.66 a	10.18 ab	10.56 ab	10.94 ab	11.47 b	
LSD – NIR $_{P<0.05}$	0.89	0.93	1.15	0.89	1.10	

Note: means differ significantly at p = 0.05 according to Tukey's HSD test are marked with different letters
Uwaga: średnie różniące się istotnie przy p = 0.05 według testu HSD Tukey'a zaznaczono różnymi literami

Table 2. Total sugars content (g 100 g^{-1} f.w.) in carrot roots during vegetation period in relation to the cultivars (means of 2006–2008)
Tabela 2. Zawartość cukrów ogółem (g 100 g^{-1} św.m.) w korzeniach marchwi w okresie wegetacji w zależności od odmiany (średnie z lat 2006–2008)

Cultivar Odmiana	Period from emerging – Okres od wschodów					Means Średnie
	7 weeks 7 tygodni	10 weeks 10 tygodni	13 weeks 13 tygodni	16 weeks 16 tygodni	19 weeks 19 tygodni	
Perfekcja	5.36	5.40	5.60	5.63	6.55	5.71
Interceptor	3.75	4.57	4.58	4.60	5.16	4.53
Vita Longa	3.96	4.60	4.58	4.80	4.90	4.57
Nebula	4.38	4.50	4.95	4.87	5.21	4.78
Deep Purple	4.12	4.40	4.52	4.74	5.00	4.56
Purple Haze	5.84	6.20	6.60	6.60	7.00	6.45
Mello Yello	3.75	4.20	4.17	4.43	4.58	4.23
White Satin	3.73	4.60	4.90	4.90	4.90	4.61
Means – Średnia	4.36 a	4.81 b	4.99 b	5.07 b	5.41 c	
LSD – NIR $_{P<0.05}$	0.72	0.81	0.62	0.80	0.93	

Note: see tab. 1 – Uwaga: zob. tab. 1.

Total sugar content in storage roots was differentiated among the cultivars in all terms of observations (tab. 2). The content changed during vegetation period from 3.7–5.8 g 100 g^{-1} in the 7^{th} week after emerging to 4.6–7.0 g 100 g^{-1} in 19^{th} week after emerging. `Purple Haze` showed the highest content of sugars in each term. Sugars content increased during plants vegetation. The highest increase of the content was found for `Interceptor`. Similar relationship between harvest term and content of sugars in carrot roots reported Nilsson [1987] and Gajewski et al. [2009].

Soluble solids content in carrot roots showed strong increasing tendency during vegetation period (tab. 3). At the beginning of plant growth soluble solids content in the roots varied from 6.05 to 7.73 °Bx, depending on the cultivar, and at the end of vegetation reached 7.73–10.58 °Bx. Relatively the lowest soluble solids content in each term of harvest was found in the roots of `White Satin`, and the highest content in the roots of 'Purple Haze`. The biggest differences between cultivars in respect of soluble solids content were noticed for the last term of harvest. The highest dynamics of soluble solids accumulation in storage roots was shown by `Deep Purple` cv. Generally, soluble solids content in the roots was higher than sugars content.

Table 3. Soluble solids content (°Bx) in carrot roots during vegetation period in relation to the cultivars (means of 2006–2008)
Tabela 3. Zawartość ekstraktu (°Bx) w korzeniach marchwi w okresie wegetacji w zależności od odmiany (średnie z lat 2006–2008)

Cultivar Odmiana	Period from emerging – Okres od wschodów					Means Średnie
	7 weeks 7 tygodni	10 weeks 10 tygodni	13 weeks 13 tygodni	16 weeks 16 tygodni	19 weeks 19 tygodni	
Perfekcja	6.75	6.93	8.03	8.70	9.50	7.98
Interceptor	7.00	7.43	8.40	9.15	9.58	8.31
Vita Longa	6.25	6.43	7.10	7.70	8.73	7.24
Nebula	6.45	7.35	7.60	8.25	8.43	7.62
Deep Purple	6.65	7.33	8.08	9.30	9.63	8.20
Purple Haze	7.73	8.43	9.95	10.28	10.58	9.39
Mello Yello	6.83	8.03	8.35	8.63	9.43	8.25
White Satin	6.05	6.65	7.13	7.50	7.73	7.01
Means – Średnia	6.71 a	7.32 b	8.08 c	8.69 d	9.20 e	
LSD – NIR $_{P<0.05}$	1.11	0.91	0.8	1.13	0.82	

Note: see tab. 1 – Uwaga: zob. tab. 1.

Investigated carrot cultivars were characterized by different content of carotenoid compounds in the roots (tab. 4). The highest content of carotenoids at the beginning and at the end of vegetation period was characteristic of `Purple Haze` and `Interceptor`, and the lowest content of `Mello Yello` and `Deep Purple`. High carotenoid compounds concentration in the roots of purple coloured carrot cultivars reported also Alasalvar et al. [2005]. We found that the amount of these compounds in carrots was related to longevity of vegetation period. For most cultivars, the highest carotenoids content was found in the 16^{th} week of vegetation, i.e. in mid-September. After that term, carotenoids content in the roots decreased slightly.

Table 4. Total carotenoid content (mg 100 g^{-1} f.w.) in carrot roots during vegetation period in relation to the cultivars (means of 2006–2008)
Tabela 4. Zawartość karotenoidów ogółem (mg 100 g^{-1} św.m.) w korzeniach marchwi w okresie wegetacji zależności od odmiany (średnie z lat 2006–2008)

Cultivar Odmiana	Period from emerging – Okres od wschodów				Means Średnie
	10 weeks 10 tygodni	13 weeks 13 tygodni	16 weeks 16 tygodni	19 weeks 19 tygodni	
Perfekcja	3.48	6.34	5.14	5.03	5.00
Interceptor	7.38	10.82	7.13	6.56	7.97
Vita Longa	4.62	3.28	6.66	3.24	4.45
Nebula	3.11	7.33	6.76	1.98	4.80
Deep Purple	1.32	2.96	1.34	0.26	1.47
Purple Haze	7.74	10.33	14.29	10.63	10.75
Mello Yello	0.83	1.46	1.61	0.53	1.11
White Satin	0.43	0.00	0.65	0.04	0.28
Means – Średnia	3.61 a	5.31 b	5.45 b	3.53 a	
LSD – NIR $_{P<0.05}$	2.12	2.37	2.67	1.98	

Note: see tab. 1 – Uwaga: zob. tab. 1.

Nitrates content in carrot roots during the vegetation period was significantly differentiated among the cultivars (tab. 5). The highest nitrates content at the beginning of vegetation was found for `White Satin` and `Purple Haze`, and for the last term of observation for `Mello Yello` as well. The differences in nitrates accumulation by different carrot cultivars were reported [Gutezeit and Fink 1999, Gajewski et al. 2009]. On average, nitrates content showed slight decreasing tendency during carrot growth. At the last harvest term nitrates content was the lowest. This is in agreement with results obtained by Mazur [1992], Gutezeit [1999] and Gajewski et al. [2009]. In our study, the highest nitrates amount observed did not exceed the value of 400 mg NO_3 kg^{-1} f.w., which is permitted in Poland for raw carrot [Anonymous 2003].

Table 5. Nitrates content (mg NO_3 kg^{-1} f.w.) in carrot roots during vegetation period in relation to the cultivars (means of 2006–2008)
Tabela 5. Zawartość azotanów (mg NO_3 kg^{-1} św.m.) w korzeniach marchwi w okresie wegetacji w zależności od odmiany (średnie z lat 2006–2008)

Cultivar Odmiana	Period from emerging – Okres od wschodów					Means Średnie
	7 weeks 7 tygodni	10 weeks 10 tygodni	13 weeks 13 tygodni	16 weeks 16 tygodni	19 weeks 19 tygodni	
Perfekcja	159	112	114	152	205	148
Interceptor	297	134	122	135	150	168
Vita Longa	237	179	128	181	192	183
Nebula	144	230	159	147	127	161
Deep Purple	260	273	196	201	167	219
Purple Haze	351	331	311	349	223	313
Mello Yello	302	289	248	242	239	264
White Satin	339	379	327	278	246	314
Means – Średnia	261 b	241 b	201 a	211 a	194 a	
LSD – NIR $_{P<0.05}$	87	78	98	65	59	

Note: see tab. 1 – Uwaga: zob. tab. 1.

The determination coefficients R^2 for relationship between increasing of mass of the storage root during plant growth and chemical compounds accumulation in the root were calculated and are shown in table 6. The highest values of the coefficient (above 80%, on average) are characteristic of dry matter, sugars and soluble solids contents. Therefore, it can be concluded that there is a strict relationship between roots mass increasing during growth and those compounds accumulation. However, differences between carrots of investigated cultivars in respect of the significance for the relationship was found. For example, 'Perfekcja' was the cultivars showed a lower level of the relationship (R^2 value below 80%) for dry matter and 'Interceptor' for sugars content. The correlations for carotenoid compounds and nitrates accumulations are not so strong, and much differentiated among cultivars taken to the experiment.

Table 6. Determination coefficients R^2 (%) for relationship between mass of carrot roots and chemical compounds content
Tabela 6. Współczynniki determinacji R^2 (%) dla zależności między masą korzenia marchwi a zawartością składników chemicznych

Cultivar Odmiana	Dry matter Sucha masa	Sugars Cukry	Soluble solids Ekstrakt	Carotenoids Karotenoidy	Nitrates Azotany
Perfekcja	78.3	90.2	95.1	14.2	42.5
Interceptor	84.8	71.0	94.7	31.6	42.4
Vita Longa	85.1	85.6	91.0	0.2	14.7
Nebula	98.4	89.1	97.2	1.0	18.2
Deep Purple	95.6	95.0	99.1	26.2	76.2
Purple Haze	89.0	94.3	98.5	52.6	36.4
Mello Yello	88.1	95.9	98.7	7.1	84.9
White Satin	93.0	80.0	97.6	1.3	60.3
Mean – Średnio	89.0	87.6	96.5	16.8	47.0

Table 7. Determination coefficients R^2 (%) for relationship between dry matter of carrot roots and chemical compounds content
Tabela 7. Współczynniki determinacji R^2 (%) dla zależności między suchą masą korzenia marchwi a zawartością składników chemicznych

Cultivar Odmiana	Sugars Cukry	Soluble solids Ekstrakt	Carotenoids Karotenoidy	Nitrates Azotany
Perfekcja	78.4	94.2	3.6	45.2
Interceptor	95.8	78.8	46.4	66.9
Vita Longa	65.3	95.6	9.3	3.1
Nebula	84.9	98.4	6.1	12.1
Deep Purple	96.5	94.4	20.4	82.2
Purple Haze	95.2	89.9	28.6	58.2
Mello Yello	79.5	87.1	11.5	77.2
White Satin	91.6	96.4	04.8	48.3
Mean – Średnio	85.9	91.9	16.3	49.2

The determination coefficients R^2 for relationship between increasing of dry matter in the storage root and chemical compounds accumulation in the root were also calculated (tab. 7). The highest values of the coefficient (above 80%, on average) were found for sugars and soluble solids contents. It seems therefore that the accumulation of carotenoid compounds and nitrates in carrot storage roots does not strictly relate to dry matter changes during vegetation period.

CONCLUSIONS

1. The accumulation of dry matter, sugars and soluble solids in storage roots of all cultivars showed increasing tendency during the plants vegetation period, but significant differences between the cultivars in the chemical composition of the roots in all terms of harvest were also found.

2. The highest sugars, soluble solids and carotenoid content at the end of the vegetation period content showed roots of 'Purple Haze' carrot.

3. Dry matter, sugars and soluble solids accumulations in carrot storage roots were strongly correlated to increase of mass of the roots during the plants growth.

4. There was found strong relationship between dry matter of the storage roots and sugars or soluble solids content in the roots during vegetation period.

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GROMADZENIE SKŁADNIKÓW CHEMICZNYCH W KORZENIACH SPICHRZOWYCH PRZEZ MARCHEW RÓŻNYCH ODMIAN PODCZAS OKRESU WEGETACJI

Streszczenie W latach 2006–2008 przeprowadzono doświadczenie polowe nad wpływem długości okresu wegetacji na gromadzenie się składników chemicznych w korzeniach spichrzowych marchwi odmian o zróżnicowanej barwie i kształcie korzenia. Obiektem badań była marchew odmian ‘Perfekcja’, ‘Interceptor’, ‘Vita Longa’, ‘Nebula’, ‘Purple Haze’, 'Deep Purple', ‘Mello Yello’ oraz 'White Satin'. W odstępach trzech tygodni badano w korzeniach zawartość suchej masy, cukrów ogółem, ekstraktu, karotenoidów ogółem oraz azotanów(V). Analizowano również zależność między masą korzeni spichrzowych marchwi a gromadzeniem się w nich składników chemicznych. Uzyskane wyniki wskazują na duże zróżnicowanie składu chemicznego korzeni badanych odmian marchwi oraz duże zmiany w ich składzie chemicznym w zależności od terminu zbioru. Najwięcej cukrów ogółem, ekstraktu oraz karotenoidów ogółem w końcowym okresie wegetacji gromadziły korzenie odmiany fioletowo-pomarańczowej 'Purple Haze'. Wykazano dużą zależność (współczynnik determinacji R^2 powyżej 80%) gromadzenia suchej masy, cukrów oraz ekstraktu w korzeniach spichrzowych od przyrostu masy korzeni spichrzowych w ciągu okresu wegetacji. Zależność ta w przypadku zawartości karotenoidów i azotanów była natomiast dużo słabsza. Stwierdzono także silną zależność suchej masy korzeni spichrzowych od zawartości w nich cukrów ogółem i ekstraktu.

Słowa kluczowe: marchew, odmiany, okres wegetacji, sucha masa, cukry, azotany(V), karotenoidy

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