Comparison of Volatiles, Phenolics, Sugars, Antioxidant Vitamins, and Sensory Quality of Different Colored Carrot Varieties

Cesarettin Alasalvar,*,[†] John M. Grigor,[†] Donglin Zhang,[†] Peter C. Quantick,[†] and Fereidoon Shahidi[‡]

Food Research Center, University of Lincolnshire and Humberside, Brayford Pool, Lincoln LN6 7TS, United Kingdom, and Department of Biochemistry, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X9, Canada

Four different colored carrots, orange, purple with orange core, yellow, and white, were examined for their content of phenolics, antioxidant vitamins, and sugars as well as their volatiles and sensory responses. A total of 35 volatiles were identified in all carrots, 27 positively. White carrot contained the highest content of volatiles, followed by orange, purple, and yellow. In total, 11, 16, 10, and 9 phenolic compounds were determined for the first time in orange, purple, yellow, and white carrots, respectively. Of these, chlorogenic acid was the most predominant phenolic compound in all carrot varieties. Differences ($p < 0.05$) in relative sweetness, the contents of vitamin C and α- and β-carotenes, and certain flavor characteristics were observed among the colored carrot varieties examined. Purple carrots contained 2.2 and 2.3 times more α- and β-carotenes (trace in yellow; not detected in white) than orange carrots, respectively. Purple carrot may be used in place of other carrot varieties to take advantage of its nutraceutical components.

Keywords: *Colored carrots; volatiles; phenolics; sugars; vitamin C; α- and β-carotenes; flavor profile*

INTRODUCTION

Healthy eating guidelines have directed the general public to eat more fresh fruit and vegetables throughout the world. Among these, carrots are being increasingly consumed (*1*), mainly due to their pleasant flavor and their perceived health benefits related to their vitamins, minerals, and fiber. Carrots have been ranked tenth in terms of nutritional value among 38 other fruits and vegetables, and seventh for their contribution to nutrition (*2*).

Carrots have a complex flavor. There is no single compound that accounts for a distinctively carrot like-flavor (*3*). There are many factors that influence carrot flavor, including nonvolatile chemical constituents such as free sugars, phosphates, and nitrogenous compounds (*4*), bitter compounds (*5*), phenolics (*6, 7*), and organic acids (*7*). However, the characteristic flavor of carrots is mainly due to the volatile constituents, which are mostly made up of terpenes and sesquiterpenes (*3, 8–16*).

Phenolic compounds in fruits and vegetables are of great interest in two respects. First, they contribute to the sensory qualities of fruits and vegetables: color, astringency, bitterness, and aroma. Second, some phenolics possess pharmacological properties and are used for therapeutic purposes (*17*). Their contribution to the resistance of fruits to parasite attack appears to be well established by earlier research (*18–20*), although their physiological function and modes of action are still being discussed. Therefore, the metabolism of phenolics may be used as a good indicator to evaluate the quality and storability of carrots.

Carrots are the major single source of provitamin A, providing 17% of the total vitamin A consumption (*21*). In carrots, six types of carotenes and related compound exist, α-, β-, γ-, and ζ-carotenes, lycopene, and β-zeacarotene. Of these, α- and β-carotenes are most predominant (*22*), which theoretically possess 50 and 100% vitamin A activity, respectively (*23, 24*). Recently, the demand for β-carotene has increased due to its reported anticancer activity in certain cases (*25, 26*) and other health benefits (*27, 28*). On the other hand, vitamin C (ascorbic acid) is the micronutrient most readily associated with fruits and vegetables. Its content varies considerably among different vegetables (*29*) and depends also on the variety and agronomic conditions (*30*).

The terpenoids and sugars in carrots are the most important sensory indicators for consumer perception of this vegetable. Simon et al. (*13*) have reported that carrot quality is determined, in part, by its sugar content, which contributes to sweetness.

To assist in the breeding programs, it is necessary to analyze typical varieties in terms of volatiles, phenolics, antioxidants, sugars, and sensory responses. These quality attributes are important for plant breeders who wish to optimize the functional health properties of a variety while ensuring attractive flavor and color of the product. The objective of this study was to ascertain if there were any differences among typical colored carrot varieties with regard to their volatiles, phenolics, antioxidants, sugars, and sensory responses.

MATERIALS AND METHODS

Carrots. Four different colored carrots, orange, purple with orange core, yellow, and white, were sown in the same location (Spalding, U.K.) in sandy, silt soil in May and were lifted for analysis in November of the same year.

Materials. β- and γ-Bisabolenes were obtained from Tokyo Kasei Organic Chemicals Ltd., Tokyo, Japan. α-Thujene and

* Corresponding author [telephone +44 (0) 1522 886024; fax +44 (0) 1522 886026; e-mail calasalvar@lincoln.ac.uk].
[†] University of Lincolnshire and Humberside.
[‡] Memorial University of Newfoundland.

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β-farnesene were obtained from Wako Chemicals Ltd., Tokyo, Japan. All other standards used for quantitation were obtained from Aldrich, Fluka, and Sigma Chemicals Ltd., Dorset, U.K., unless otherwise indicated.

Sample Preparation. Carrots (uniform size and free from blemishes) from each color (~3–5 kg) were "topped" and "tailed". The samples were then placed inside paper bags (avoiding light) and stored under chilled conditions at 2–5 °C and a relative humidity of 70–90%, until analyzed (within 1 week). All carrots were thoroughly washed with tap water and discolored spots, if present, scraped before analysis. Each carrot type was extracted, and the analytes from three samples of the original carrot batches were measured.

Headspace Volatile Analysis. Mass spectra of volatiles were obtained using a combination of a Varian Genesis headspace autosampler, Star 3400 CX GC, and Saturn GC-MS-MS 4D (Varian Associates Inc., Palo Alto, CA). Sample preparation, preparation of solutions of authentic compounds, identification and quantitation of carrot volatiles, and static headspace analysis–gas chromatography–mass spectrometry (SHA-GC-MS) were carried out according to the method of Alasalvar et al. (*16*).

Extraction and Purification of Phenolic Compounds. Phenolic compounds were extracted and purified according to the methods of Amiot et al. (*31*) and Mayen et al. (*32*) with slight modification. A 75 g sample of grated carrot was homogenized in 100 mL of cold ethanol (65%) containing sodium metabisulfite (0.5%) in an ice bath and left for 30 min when homogenized three more times intermittently. The homogenate was filtered through four layers of cheesecloth. The residue was collected, and 50 mL of the same extraction solvent was added to it. Two successive extractions were carried out. The combined supernatants were centrifuged at 7000*g* for 15 min. After removal of ethanol from the supernatant by evaporation under vacuum at 35–40 °C, pigments were eliminated by two successive extractions with petroleum ether (2:1, v/v). After the addition of ammonium sulfate (20%) and metaphosphoric acid (MPA; 2%) to the aqueous phase, phenolic compounds were extracted three times with ethyl acetate (1:1, v/v). The ethyl acetate layers were combined and evaporated to dryness under vacuum at 35–40 °C. Finally, the residue was dissolved in 10 mL of methanol and stored at −20 °C prior to high-performance liquid chromatographic (HPLC) analysis.

The chromatograph consisted of an L-6200A intelligent pump, L-4500 diode array detector (Hitachi Ltd., Tokyo, Japan), and Elonex PC 466/I computer (Elonex, Aspley Way, London, U.K.). A 10 μL sample was injected after filtration through a 0.45 μm filter. The isocratic separation was performed using a 5 μm Alltima C18 column, 250 mm × 4.6 mm i.d. (Alltech Associates Applied Science Ltd., Carnforth, U.K.). Mobile phase was solvent A [acidic water (2% acetic acid)] and solvent B [acetonitrile/methanol (10:15, v/v)]. The flow rate was 1.0 mL/min. The best separation was achieved using the following gradient elution: 0 min, 90% A and 10% B; 10 min, 80% A and 20% B; 15 min, 70% A and 30% B; 25 min, 60% A and 40% B; 30 min, 50% A and 50% B and 40 min, 50% A and 50% B. The monitoring wavelength of the diode array detector was set at 330 nm for monitoring phenolic compounds.

Identification and Quantitation of Phenolic Compounds. Identification of phenolic compounds was achieved by comparing their retention times with those of standards. UV spectra were recorded using an HPLC diode array detector; UV absorbance ratios after co-injection of samples and standards were calculated. Each phenolic compound was quantified on the basis of peak areas through comparison with a calibration curve obtained with the corresponding standard.

Sugar Analysis. Sugar (fructose, glucose, and sucrose) levels were measured according to the HPLC method of Schwarzenbach (*33*). Sugars were extracted from raw carrots (60 g) with 100 mL of acetonitrile/water (1:1, v/v) for 5 min. After filtering through Whatman No. 541 filter paper, filtrate was refiltered through a 0.45 μm filter and injected (10 μL) into an 802C Monometric module HPLC system (Gilson, Villiers, France) fitted with an ACS 750/14 mass detector (ACS, Cheshire, U.K.) and an S5 amino column, 250 mm ×

4.6 mm i.d. (Phase Separation Ltd., Queensferry, U.K.). A trio chromatography computer (Trivector, Sandy, Beds, U.K.) was used for integration. The mobile phase was a mixture of acetonitrile and water in the ratio of 80:20 (v/v) at 2 mL/min, and the detector temperature was maintained at 63 °C with photomultiplier sensitivity of 5. Fructose, glucose, and sucrose were quantified on the basis of peak areas and comparison with a calibration curve obtained with the corresponding standards.

Vitamin C (Ascorbic Acid) Analysis. Vitamin C content was measured according to the indophenol titration method (*34*). The carrots were homogenized in an MPA solution and extracted. The vitamin C was titrated against a 2,6-dichlorophenol–indophenol solution at pH 0.6 in the presence of formaldehyde, to a pink endpoint.

Carotene Analysis. α- and β-carotene contents were determined by HPLC according to the method described by Bushway (*35*). All manipulations were carried out under a gold fluorescent lighting (Thorn, U.K.) because carotenoids are highly sensitive to light, heat, and air. The chromatograph consisted of an L-6200A intelligent pump, L-4500 diode array detector (Hitachi Ltd.), and Elonex PC 466/I computer (Elonex). A 5 μL sample was injected after filtration through a 0.45 μm filter. The isocratic separation was performed using a 5 μm Vydac 218 TP54 column, 250 mm × 4.6 mm i.d. (Phenomenex, Cheshire, U.K.), with a solvent system of acetonitrile/methanol/stabilized tetrahydrofuran (40:56:4, v/v/v) at a flow rate of 1 mL/min and a monitoring wavelength of 470 nm. α- and β-carotene contents were determined on the basis of peak heights and comparison with a calibration curve obtained with the corresponding standards.

Sensory Profile Analysis. The carrots were assessed using a flavor profile method (*36*). Five previously trained descriptive panelists participated in two orientation sessions to describe carrot attributes. During these orientation experiments panelists evaluated 10 different coded carrot varieties; 9 flavor attributes were identified (standards were made available for panelists) when a consensus agreement was obtained. Panelists evaluated the intensity of the attributes independently using a 100 mm long line with descriptive terms ~10 mm from each end. Each panelist was given a whole carrot to evaluate and was requested to assess the top, bottom, and middle of the carrot and report the average of the sensory responses obtained.

Statistical Analysis. Statistical significance was checked by using a two-sample *t* test, assuming equal variances. One-way analysis of variance (ANOVA) and multiple-range least significant difference (LSD) tests for sensory profile analysis were carried out by using a statistical program (SPSS ver. 5.0) for $p < 0.05$ significance level.

RESULTS AND DISCUSSION

Volatile Compounds. A typical total ion chromatogram of volatile compounds in fresh raw orange carrots (Figure 1) showed a total of 35 volatile headspace compounds were detected. Among these, 27 were positively identified (MS and GC retention index match authentic samples) and quantified. The rest, eight volatiles, were also tentatively identified, but no attempt was made to quantify them as they contributed <1% to the total peak area. These were propanol (Figure 1, peak 1), borneol (peak 19), linalyl acetate (peak 21), β-citronellol (peak 22), α-santalene (peak 24), α-selinene (peak 27), γ-elemene (peak 31), and α-zingiberene (peak 32). In addition, among the positively identified 27 compounds, 4 volatiles [camphor (peak 18), terpinen-4-ol (peak 20), longifolene (peak 25), and valencene (peak 33)], which contributed ≤0.1% to the total peak area, are not shown in Table 1. The remaining 23 positively identified and quantified compounds will be discussed in detail (Table 1). In our previous study, we also
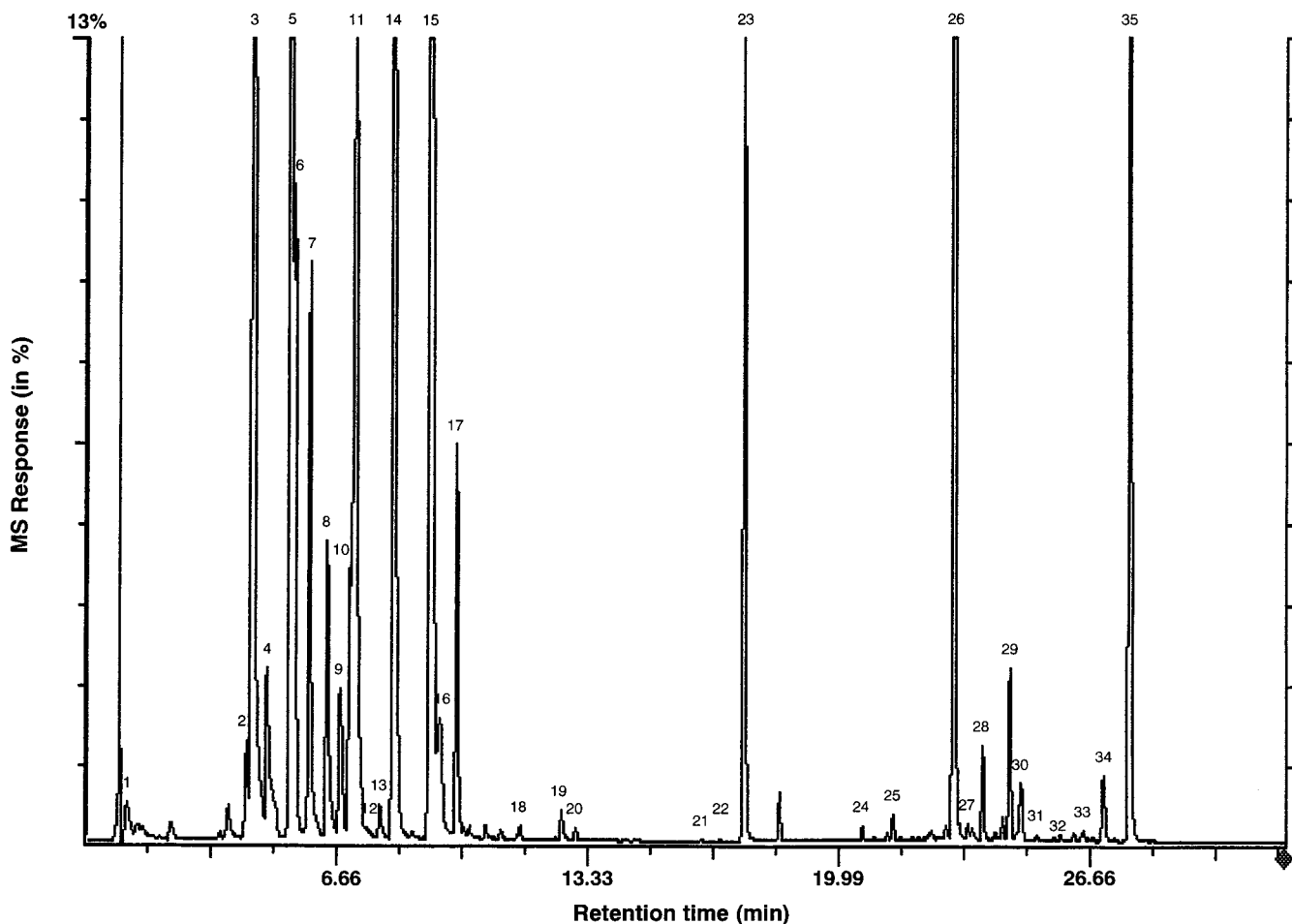
Figure 1. Typical total ion chromatograph of volatile compounds in orange carrots. Peak identification: propanol (1), α-thujene (2), α-pinene (3), camphene (4), sabinene (5), β-pinene (6), myrcene (7), α-phellandrene (8), α-terpinene (9), *p*-cymene (10), limonene (11), *cis*-ocimene (12), *trans*-ocimene (13), γ-terpinene (14), terpinolene (15), 2,5-dimethylstyrene (16), undecane (17), camphor (18), borneol (19), terpinen-4-ol (20), linalyl acetate (21), β-citronellol (22), bornyl acetate (23), α-santalene (24), longifolene (25), β-caryophyllene (26), α-selinene (27), *trans*-α-bergamotene (28), α-humulene (29), *cis*-β-farnesene (30), γ-elemene (31), α-zingiberene (32), valencene (33), β-bisabolene (34), and γ-bisabolene (35).

identified 35 different volatile compounds from seven orange carrot F1 hybrid varieties (*16*).

Fresh raw carrot volatiles mainly consisted of an alcohol (peak 1), simple monoterpenes (peaks 2–15), dimethyl-substituted styrene (peak 16), alkane (peak 17), aromatic terpene (peak 18), terpene alcohols (peaks 19, 20, and 22), terpene acetates (peaks 21 and 23), and sesquiterpenes (peaks 24–35). Mono- and sesquiterpenes accounted for ~99% of the total volatiles extracted from different colored carrots. The percentage of monoterpenes was higher than that of sesquiterpenes in all varieties. Such terpenes, which impart the characteristic and typical aroma to carrots, are considered to be the most important volatile compounds (*8–15*).

Results in Table 1 show large varietal differences for different colored carrot volatiles. Total volatiles ranged from 2.368 to 16.250 ppm, being highest in white and lowest in yellow carrots. Highly significant differences ($p < 0.01$) existed in total volatile content among different varieties. Alasalvar et al. (*16*) found sizable varietal differences in total volatiles among seven different varieties of orange carrots, varying between 4.59 and 30.93 ppm. The orange carrot variety used in this study was different from varieties used in the above study. In white carrot, the most abundant terpenoid, comprising ~45% of the total volatiles, was terpinolene,

whereas in the yellow carrot variety this volatile comprised 24% of the total. Terpinolene is the most abundant volatile terpene reported by other researchers (*8, 11, 13, 15*).

Major compounds identified included α-pinene, sabinene, myrcene, limonene, γ-terpinene, terpinolene, β-caryophyllene, and γ-bisabolene. Our findings are in good agreement with those of other studies (*7–10, 13, 15, 16*). The flavor of raw carrots has been reported as being largely influenced by genetic variation (*9, 37, 38, 42*). Simon et al. (*39*) considered the effect of different soils and climates on carrot aroma, and concluded that although soils did make a difference, genotype exerted a greater influence.

Phenolics. Figure 2 (parts A, B, C, and D, respectively) illustrates the typical chromatographic separation of phenolic compounds extracted from the orange, purple, yellow, and white carrots. All carrots studied contained mainly hydroxycinnamic acid derivatives, namely 3′-caffeoylquinic acid (neochlorogenic acid), 5′-caffeoylquinic acid (chlorogenic acid), 3′-*p*-coumaroylquinic acid (3′-pCQ), 3′-feruloylquinic acid (3′-FQ), 3′,4′-dicaffeoylquinic acid (3′,4′-DCQ), 5′-feruloylquinic acid (5′-FQ), 5′-*p*-coumaroylquinic acid (5′-pCQ), 4′-feruloylquinic acid (4′-FQ), 3′,5′-dicaffeoylquinic acid (3′,5′-

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Table 1. Levels of Volatile Compounds in Different Raw Carrot Varieties[a]

peak[b]	compound	levels of volatile compounds (ppm)			
		orange	purple	yellow	white
2	α-thujene	0.001 ± 0.000	tr[c]	0.013 ± 0.002	0.046 ± 0.003
3	α-pinene	0.180 ± 0.026	0.017 ± 0.006	0.018 ± 0.004	1.242 ± 0.073
4	camphene	0.005 ± 0.001	0.002 ± 0.001	tr	0.065 ± 0.006
5	sabinene	0.023 ± 0.002	0.001 ± 0.000	0.537 ± 0.063	1.624 ± 0.089
6	β-pinene	0.089 ± 0.014	0.043 ± 0.007	0.103 ± 0.013	0.597 ± 0.051
7	myrcene	0.351 ± 0.042	0.494 ± 0.192	0.196 ± 0.019	0.791 ± 0.130
8	α-phellandrene	0.170 ± 0.010	0.066 ± 0.005	0.081 ± 0.004	0.326 ± 0.032
9	α-terpinene	0.010 ± 0.001	0.002 ± 0.001	0.020 ± 0.004	0.116 ± 0.028
10	*p*-cymene	0.057 ± 0.014	0.017 ± 0.008	0.004 ± 0.001	0.209 ± 0.068
11	limonene	0.236 ± 0.039	0.066 ± 0.008	0.049 ± 0.007	0.638 ± 0.073
12	*cis*-ocimene	0.103 ± 0.011	0.013 ± 0.002	nd[d]	0.041 ± 0.004
13	*trans*-ocimene	0.016 ± 0.004	0.001 ± 0.001	tr	0.004 ± 0.002
14	γ-terpinene	0.569 ± 0.096	0.056 ± 0.014	0.044 ± 0.008	1.210 ± 0.090
15	terpinolene	3.465 ± 0.354	0.810 ± 0.135	0.569 ± 0.088	7.290 ± 0.760
16	2,5-dimethylstyrene	0.079 ± 0.012	0.012 ± 0.003	0.007 ± 0.001	0.205 ± 0.021
17	undecane	0.023 ± 0.005	0.004 ± 0.001	0.001 ± 0.000	0.005 ± 0.002
23	bornyl acetate	tr	nd	tr	0.098 ± 0.006
26	β-caryophyllene	0.749 ± 0.060	1.025 ± 0.090	0.332 ± 0.014	1.251 ± 0.018
28	*trans*-α-bergamotene	0.023 ± 0.002	0.010 ± 0.001	0.011 ± 0.001	0.022 ± 0.000
29	α-humulene	0.035 ± 0.001	0.052 ± 0.005	0.014 ± 0.002	0.061 ± 0.003
30	*cis*-β-farnesene	0.006 ± 0.000	0.008 ± 0.001	0.012 ± 0.001	0.001 ± 0.001
34	β-bisabolene	0.054 ± 0.005	0.007 ± 0.001	0.019 ± 0.001	0.064 ± 0.005
35	γ-bisabolene	0.424 ± 0.024	0.245 ± 0.024	0.338 ± 0.006	0.344 ± 0.021
	monoterpenes	5.275 (79.11)[e]	1.588 (53.81)	1.634 (69.00)	14.199 (87.38)
	sesquiterpenes	1.291 (19.36)	1.347 (45.65)	0.726 (30.66)	1.743 (10.73)
	total volatiles	6.668 ± 0.576[f]	2.951 ± 0.261[g]	2.368 ± 0.220[h]	16.250 ± 1.177[i]

[a] Data are expressed as mean ± SD of three determinations on a fresh weight basis. [b] Peak numbers correspond to the peaks in Figure 1. [c] tr, trace (<0.001 ppm). [d] nd, not detected. [e] Numbers in parentheses indicate percent of compounds in the total amount of volatiles. [f–i] Means ± SD followed by the same letter, within a row, are not significantly different ($p > 0.05$). Compounds with ≤1% total peak area are not shown. These include positively (peaks 18, 20, 25, and 33) and tentatively (peaks 1, 19, 21, 22, 24, 27, 31, and 32) identified compounds (see Figure 1).
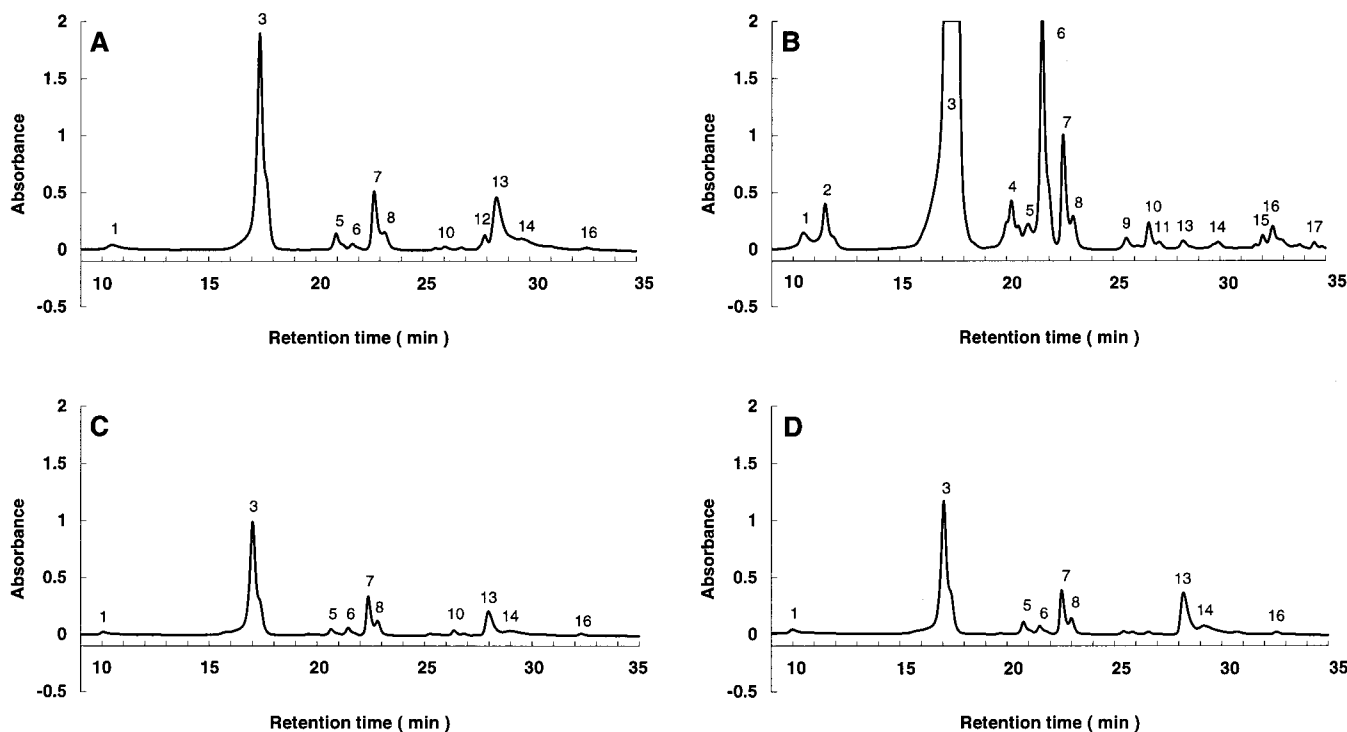
Figure 2. Typical chromatographs of phenolic compounds in orange (A), purple (B), yellow (C), and white (D) carrot varieties.

DCQ), 3′,4′-diferuloylquinic acid (3′,4′-DFQ), and 3′,5′-diferuloylquinic acid (3′,5′-DFQ).

In total, 11 phenolic compounds (UV spectra and HPLC retention times matched authentic samples) were defined, except isochlorogenic acid, in orange carrots. On the other hand, Sarkar and Phan (*6*) identified two phenolic compounds in orange carrot root (caffeic acid,

isochlorogenic and chlorogenic acids, and four unknowns). It is also most interesting to note the presence of dicaffeoylquinic acid (DCQ), especially in orange carrots. This compound may exert a very strong antioxidant activity in the product.

The quantitative values for the content of phenolics in colored carrot varieties are listed in Table 2. The total

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Table 2. Levels of Phenolic Compounds in Different Raw Carrot Varieties[a]

peak[b]	symbol	compound	levels of phenolic compounds (mg/100 g)			
			orange	purple	yellow	white
1	3′-CQ	3′-caffeoylquinic acid	0.28 ± 0.02^d	0.88 ± 0.05^c	0.09 ± 0.01^e	0.09 ± 0.01^e
2	c-3′-CQ	*cis*-3′-caffeoylquinic acid	nd[g]	1.94 ± 0.10	nd	nd
3	5′-CQ	5′-caffeoylquinic acid	8.50 ± 0.24^d	54.08 ± 3.10^c	4.41 ± 0.21^e	4.47 ± 0.20^e
4		caffeic acid	nd	2.42 ± 0.16	nd	nd
5	3′-pCQ	3′-*p*-coumaroylquinic acid	0.54 ± 0.02^d	0.91 ± 0.06^c	0.20 ± 0.02^f	0.31 ± 0.02^e
6	3′-FQ	3′-feruloyquinic acid	0.21 ± 0.02^{def}	7.30 ± 0.20^c	0.19 ± 0.01^f	0.26 ± 0.02^{de}
7	3′,4′-DCQ	3′,4′-dicaffeoylquinic acid	2.08 ± 0.15^d	2.78 ± 0.18^c	1.30 ± 0.07^e	1.06 ± 0.06^f
8	5′-FQ	5′-feruloyquinic acid	0.11 ± 0.01^f	0.96 ± 0.03^c	0.51 ± 0.03^d	0.39 ± 0.02^e
9	c-5′-CQ	*cis*-5′-caffeoylquinic acid	nd	0.49 ± 0.02	nd	nd
10	5′-pCQ	5′-*p*-coumaroylquinic acid	0.13 ± 0.01^d	0.74 ± 0.03^c	0.11 ± 0.01^d	nd
12	4′-FQ	4′-feruloyquinic acid	0.40 ± 0.03	nd	nd	nd
13	3′,5′-DCQ	3′,5′-dicaffeoylquinic acid	3.80 ± 0.20^c	0.44 ± 0.02^f	0.75 ± 0.02^e	1.74 ± 0.09^d
14	3′,4′-DFQ	3′,4′-diferuloylquinic acid	0.07 ± 0.01^e	0.53 ± 0.03^c	0.12 ± 0.01^e	0.31 ± 0.02^d
16	3′,5′-DFQ	3′,5′-diferuloylquinic acid	0.09 ± 0.01^d	1.17 ± 0.02^c	0.04 ± 0.01^d	0.06 ± 0.01^d
		total phenolics	16.21 ± 0.21^d	74.64 ± 3.32^c	7.72 ± 0.22^e	8.69 ± 0.24^e

[a] Data are expressed as mean $\pm$ SD of three determinations on a fresh weight basis. [b] Peak numbers correspond to the peaks in Figure 2. Peaks 11, 15, and 17 are unkown compounds. [c–f] Means $\pm$ SD followed by the same letter, within a row, are not significantly different ($p > 0.05$). [g] nd, not detected.

Table 3. Content of Sugars, Vitamin C, and α- and β-Carotenes in Different Raw Carrot Varieties[a]

color	sugars (g/100 g)				relative sweetness[b]	vitamin C (mg/100 g)	α-carotene (μg/100 g)	β-carotene (μg/100 g)
	fructose	glucose	sucrose	total				
orange	1.34 ± 0.04^c	1.44 ± 0.06^c	2.69 ± 0.13^c	5.47 ± 0.10^c	6.07 ± 0.09^d	5.33 ± 0.36^c	3990 ± 912^c	6935 ± 208^c
purple	0.58 ± 0.03^d	0.69 ± 0.09^d	4.11 ± 0.23^d	5.38 ± 0.29^c	5.62 ± 0.26^c	nm[g]	8725 ± 811^d	16130 ± 593^d
yellow	1.31 ± 0.19^c	1.77 ± 0.21^c	1.96 ± 0.11^{ef}	5.04 ± 0.49^c	5.54 ± 0.57^{cd}	1.98 ± 0.06^d	tr[h]	tr
white	1.47 ± 0.14^c	1.59 ± 0.19^c	2.33 ± 0.31^{cf}	5.39 ± 0.47^c	6.05 ± 0.50^{cd}	1.25 ± 0.09^e	nd[i]	nd

[a] Data are expressed as mean $\pm$ SD of three determinations on a fresh weight basis. [b] Relative sweetness was calculated relative to sucrose (fructose, 1.73; glucose, 0.74; and sucrose, 1.00). [c–f] Means $\pm$ SD followed by the same letter, within a column, are not significantly different ($p > 0.05$). [g] nm, not measured (due to pink color). [h] tr, trace. [i] nd, not detected.

amount of phenolics in purple carrots was 74.64 mg/ 100 g, whereas the corresponding values in orange, yellow, and white varieties ranged from 7.72 to 16.21 mg/100 g. According to Sarkar and Phan (*6*), the total phenolics of carrots stored at 3 $\pm$ 1 °C and at ~90% relative humidity increased steadily with storage time.

Chubey and Nylund (*40*) suggested that carrots richer in phenolics are more susceptible to browning, but their contribution in fruits and vegetables for resisting parasitic attack could be of benefit to minimally processed carrots stored under modified atmosphere packaging.

The compounds 3′,4′-DCQ and 3′,5′-DCQ were the major compounds identified in orange, yellow, and white carrots. However, higher contents ($p < 0.05$) of C-3′-CQ, chlorogenic acid, caffeic acid, 3′-FQ, 3′,4′-DCQ, and 3′,5′-DFQ were found in purple carrots than in other varieties. Chorogenic acid represented 52.4, 57.1, 51.4, and 72.5% of the total phenolic compounds in orange, yellow, white, and purple carrots, respectively. However, purple carrot contained about 6.4, 12.1, and 12.3 times more chlorogenic acid than orange, white, and yellow carrots, respectively. Babic et al. (*41*) suggested that the level of chlorogenic acid was related to the storage behavior of shredded carrots. We suggest that the purple and orange carrots could have better storage behavior than white and yellow varieties.

Sugars. Table 3 shows the content of sugars, vitamin C, and α- and β-carotenes in different raw carrot varieties. Sucrose was the predominant sugar in carrots (1.96–4.11 g/100 g), followed by glucose (0.69–1.77 g/100 g) and fructose (0.58–1.47 g/100 g). Although some sizable varietal differences ($p < 0.05$) were observed among sucrose, glucose, and fructose, no significant differences ($p > 0.05$) existed in total sugars content, which ranged from 5.04 (yellow) to 5.47 (orange) g/100

g. Simon (*3*) reported that total sugar content ranged from 3 to 8%, with sucrose predominating and lesser amounts of glucose and fructose. The sugar contents of carrot are influenced by genotype and environment (*13*, *39*, *42*). Evidence for strong genetic control of total sugar content is encouraging in establishing carrot breeding goals for increased sweetness or sugar production (*39*). Although sugars are not alone in accounting for variation in the sweetness of raw carrots, higher sugar levels and increased sweetness are desirable factors for improving carrot quality (*3*).

Vitamin C. Vitamin C content varied between 1.25 and 5.33 mg/100 g, being lowest in white and highest in orange varieties. Favell (*29*) found 2.8–4.5 mg/100 g ascorbic acid in fresh carrots. Old raw carrots are quoted as having 6 mg of ascorbic acid/100 g (*43*). The slightly higher values in the literature are due to the inclusion of dehydroascorbic acid in the ascorbic acid values. In addition, genotype differences may also contribute to the magnitude of differences observed.

In a previous study, seven orange carrot F1 hybrid varieties were analyzed for their vitamin C content using the same method (*44*) as in fresh raw carrots. The ascorbic acid content of the F1 orange hybrid analyzed in this study falls within this range; however, the yellow and white carrot varieties had significantly lower values (1.98 and 1.25 mg/100 g, respectively) and might be indicative of the β-carotene, which is present only at trace levels in the yellow and not detected in the white varieties, acting as an antioxidant.

Carotene. Simon and Wolff (*22*) have shown that the amount of α-carotene and β-carotene in carrots may vary from 13 to 40% and from 44 to 79% of the total carotenoids, respectively. Therefore, only α- and β-carotenes were quantified due to their relatively high
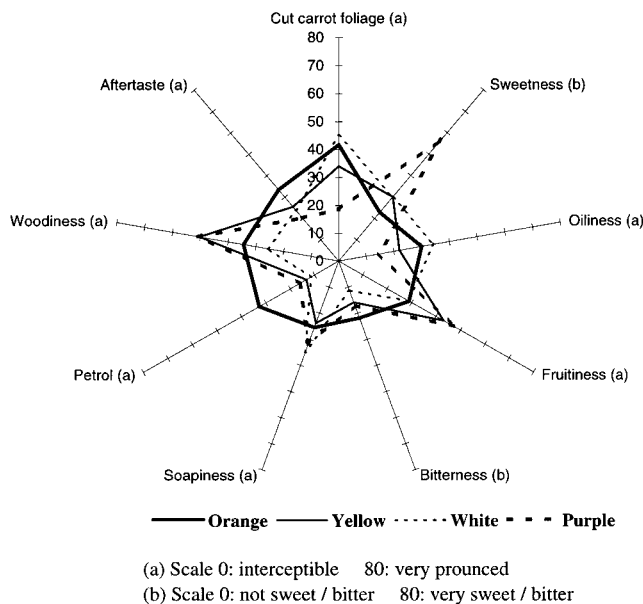
Chemical Components and Sensory Quality of Carrots

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(a) Scale 0: interceptible   80: very prounced
(b) Scale 0: not sweet / bitter   80: very sweet / bitter

Figure 3. Flavor profile analysis of colored carrot varieties.

abundance, as compared to other carotenes present in carrots. The range of α- and β-carotenes was from 3990 to 8725 μg/100 g and from 6935 to 16130 μg/100 g, respectively. Purple carrot contained 2.2 and 2.3 times more α- and β-carotenes than orange carrot. Although purple and orange carrots contained high amounts of α- and β- carotenes, only trace amounts of them were detected in yellow carrot and none was found in white carrot. In our previous study, we studied α- and β-carotene contents in seven orange carrot F1 hybrid varieties and found that the range of α- and β-carotenes was from 5197 to 7550 μg/100 g and from 9940 to 11882 μg/100 g, respectively (*44*). The orange carrot variety used in this study was different from varieties used in the above study. The results for orange carrot were similar to those reported in the literature (*23*, *35*, *45*, *46*).

Hart and Scott (*46*) reported that the content of carotenoids may be affected by variety, maturity, growing conditions, growing season, and the part of the root sampled (the outer part of the carrots contains twice as much β-carotene as the inner part). Although climate had a major influence on carotenoid content, soil and genetic factors also influenced the variability of carotenoids in carrots (*39*).

Sensory Evaluation. Figure 3 displays the sensory profile analysis of different colored carrot varieties. The flavor characteristic, namely, "cut carrot foliage", "petrol", and "sweetness", showed a significant difference among groups (p <0 .05). Other flavor characteristics showed no significant difference among groups (p > 0.05). The "cut carrot foliage" flavor attribute was more pronounced in the white and orange varieties when compared to that of the purple variety (p < 0.05). The orange variety also demonstrated a more intense "petrol" note than all other varieties (p < 0.05). Furthermore, "oiliness" was more intense in the orange and white varieties, although this was not proved to be significant. Orange and white varieties had higher levels of terpenes than the other two varieties (Table 1); thus, it may be reasonable to surmise that the flavor notes of "oiliness", "cut carrot foliage", and "petrol" are likely to be generated by terpenes, whereas "bitterness", "soapy", "woodi-

ness", and "fruitiness" are likely to be effected by other carrot constituents or contaminants.

With respect to sweetness, the purple carrot was significantly sweeter than the other three varieties (p < 0.05). This may be due to the high sucrose level found in the purple variety (Table 3). However, this observation does not agree with the total sugar contents and consideration of their relative sweetness, indicating that other carrot components may be influencing the sweetness response. It has been found by Howard et al. (*7*) and Simon et al. (*13*) that high levels of terpenoids in orange carrot mask the overall sweetness response. As mentioned above, we found higher levels of terpenes in orange and white varieties. This could be one of the reasons why purple carrot (with low relative levels of terpenoids) was significantly sweeter than the orange and white varieties. However, any further explanation will require consideration of the results of the yellow variety, which are more difficult to interpret using this line of thinking.

Conclusions. The present study demonstrated that purple carrot possesses improved quality and sensory attributes compared to orange, white, and yellow varieties. Therefore, purple carrot may be used in place of other carrot varieties in order to take advantage of its nutraceutical components.

ABBREVIATIONS USED

SHA, static headspace analysis; GC-MS, gas chromatography–mass spectrometry; HPLC, high-performance liquid chromatography; SD, standard deviation; ANOVA, analysis of variance; LSD, least significant difference.

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