Tomato Flavor and Aroma Quality as Affected by Storage Temperature

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ABSTRACT: Studies were conducted to describe flavor and aroma in ripe tomatoes stored at 5, 10, 12.5 and 20 °C. Fruit stored for 2 d below 20 °C were rated by trained sensory panelists as significantly lower ($P < 0.05$) in ripe aroma, tomato flavor, compared to those stored at 20 °C. Fruit stored at 5 °C for 4 d were rated significantly lower in ripe aroma, sweetness, tomato flavor, and significantly higher in sourness, compared to those stored at 20 °C. Following 8 and 12 d storage, fruit at 5 °C were rated lowest in ripe aroma and sweetness. Significant reductions in important GC aroma volatiles and chemical composition and electronic nose analyses concurred with sensory descriptor ratings.

Key words: *Lycopersicon esculentum* Mill., descriptive sensory analysis, tomato aroma, electronic nose, multivariate discriminant analysis

Introduction

OVER THE LAST 20 YEARS THERE HAVE BEEN NUMEROUS PUBLICATIONS reporting increased consumer dissatisfaction with fresh market tomato (*Lycopersicon esculentum* Mill.) flavor. Researchers have proposed several reasons for the inferior flavor in fresh market tomatoes. Commercial breeding programs have emphasized disease resistance, productivity, and fruit firmness in selections at the expense of flavor and texture qualities (Baldwin and others 1992). However, the influence of commercial postharvest handling practices and storage temperatures on ripe tomato flavor quality are poorly understood.

Tomatoes will incur significant chilling injury (CI) from postharvest exposure to temperatures below 13 °C. CI symptoms in tomato include uneven or partial ripening, fruit softening, increased susceptibility to postharvest fungal pathogens, reduced flavor, and surface pitting (Hobson 1987). The extent of injury depends on the storage temperature, the period of time fruits are exposed to that temperature, and the stage of fruit ripeness. Most commercial storage temperature recommendations have been formulated as a result of chilling injury studies, based on threshold temperatures not inducing the development of visual CI symptoms or major compositional changes (Hobson 1981). Green and breaker stage fruits (< 10% red coloration, USDA 1976) are considered more susceptible to chilling temperature than ripe fruits (Autio and Bramlage 1986). Red-ripe fruit have been shown to withstand low temperature storage for longer periods of time without CI symptoms (Cook and others 1958). However, storage at recommended temperatures of 10 °C to 13 °C might have a significant effect on tomato flavor even before any visual injury symptoms are expressed.

During tomato fruit ripening, a series of quantitative and qualitative changes take place, changing tomato flavor and aroma volatile profiles. Organic acids, soluble sugars, amino acids, pigments, and over 400 aroma compounds contribute to characteristic tomato flavor (Petro-Turza 1987). Because of the diversity of biosynthetic pathways contributing to the formation of volatile compounds, tomato aroma could be a good indicator of fruit injury as a result of postharvest handling treatments. Previous tomato flavor studies utilizing descriptive sensory panels have employed descriptors to verbalize sensory attributes such as sweetness, sourness, off-flavors, tomato-like (Kader and others 1977), saltiness, grassiness, stemminess, bitterness (Watada and Aulenbach 1979), overall intensity, juiciness (Resureccion and Shewfelt 1985), acidity/sourness (Kavanagh and others 1986). The use of an electronic nose combined with pattern recognition methods has been useful as a nondestructive tool to screen inferior flavored fruit and to identify postharvest handling scenarios that affect flavor quality without the appearance of any visual injury symptoms (Maul and others 1998; Benady and others 1995). Electronic nose sensors adsorb volatile molecules present in the headspace over a sample of interest, thus influencing their electrical conductivity capabilities. Given enough sensors, each sample will create a response as unique as a fingerprint (Benady and others 1995).

Commercial harvesting practices and postharvest handling procedures for fresh market tomatoes also play an important role in tomato flavor. Postharvest abuses, such as harvesting immature fruit, mechanical injury during sorting and packing, and improper temperature management have been related to altered aroma volatile profiles and altered flavor perception (Sargent and others 1997; Moretti and others 1998). Evidence of the adverse effects of low temperature storage on tomato flavor has been published previously (Kader and others 1978; Stern and others 1994; McDonald and others 1996). However, the effects of currently recommended storage temperatures on flavor and aroma have not been thoroughly addressed.

These studies were carried out to quantify the flavor and aroma changes occurring in ripe-harvested tomatoes stored for up to 12 d at 5 ° to 20 °C using a trained, descriptive sensory panel, chemical composition assays, electronic nose sensor array (EN), and gas chromatographic (GC) aroma volatile profiles.

Materials and Methods

Plant Materials

Commercially planted tomato fruits (*Lycopersicon esculentum cv.* 'Solimar' and 'BHN-189') were harvested from commercial fields in Gainesville and Quincy, Fla., U.S.A. during fall, 1997. Tomatoes were harvested at the light-red stage (Stage 5, > 90% red coloration, USDA 1976), washed, sorted for defects, and randomly divided into 4 groups (nr = 50 fruits/group).

Storage Treatments

Each group of 50 tomatoes was placed at one of 4 storage temperatures: 20 °C, 12.5 °C (recommended temperature for green and breaker stage fruit), 10 °C (recommended for red-ripe fruit), and 5 °C (typical household refrigerator temperature). Samples of 9 to 10 fruits from each temperature treatment were removed after 2 and 8 d ('BHN-189') or 4, 8, and 12 d of storage ('Solimar'). Tomatoes were removed from the different temperature treatments and placed at 20 °C approximately 6 h prior to sensory analysis. At the time of sensory analysis, tomato fruit were at the table-ripe stage, defined as 100% red coloration with a 3-5 mm deformation, as determined by a constant 9.8-N force applied for 5 sec (Gull, 1980).

Sensory Evaluation

To organize and train a descriptive sensory panel, a group of 20 volunteers showing no dislike for tomatoes were screened for proper sensory responses in recognition of citric acid and sucrose solutions of varying concentrations. Over a period of 3 mo, and a total of 12 weekly 30 min sessions, the group was reduced to 16 panelists, (10 males and 6 females; ages between 20 and 65 years old) who were trained to describe flavor and aroma attributes for fresh market tomatoes. Panelist training was limited to a 3 mo period because 15 of the 16 panelists had been involved as members of trained descriptive panels for peanuts and strawberries prior to participating in the tomato panel.

During the training sessions, panelists were presented with a variety of tomato samples representing different ripeness stages, storage temperatures and cultivars on characteristic tomato flavor. No artificial tomato flavors or individual aroma compound samples were used as training tools since the objective of the study was to assess flavor and aroma differences due to storage temperature and not to identify, through sensory analysis, individual compounds responsible for eliciting differences. The panel leader compiled a descriptor list from published literature on tomato flavor to aid panelists in verbalizing flavor and aroma characters perceived in the samples. The panel reached a consensus on 5 flavor attributes (typical tomato, sweetness, sourness, green/grassy, and off-flavor) and two aroma attributes (ripe tomato and off-odor). To avoid bias in the results, the panel leader did not influence panelists into including more attributes to describe tomato flavor and aroma. Descriptor intensity was rated using a 15 cm, unstructured line scale with a low intensity on the 15 (left) side and high intensity on the 150 (right) side as anchor terms.

Approximately 20 min before sensory analysis, whole tomato fruit samples were chopped into a coarse puree using 8 to 10 pulses of a food processor. Two tablespoons (40 to 50 g) of tomato puree were placed in 113-mL plastic cups, sealed with lids and labeled with a two-digit random number. Tomato samples were at room temperature (about 23 °C) at time of sensory analysis. Evaluations were conducted in individual booths with dim lighting and samples were presented in random order. Panelists were instructed to open the lid from each tomato sample cup to rate the aroma descriptors, then to proceed with the flavor descriptors. Water and unsalted crackers were provided for panelists to cleanse their palates in between samples. In any given session, panelists were asked to rate the flavor attributes of 4 to 6 tomato samples.

During sensory analysis, 4- 40-mL samples of tomato homogenate for GC and EN analyses were combined with 10 mL of a saturated $CaCl_2$ solution, blended at high speed for 10 sec and flash-frozen with liquid nitrogen. $CaCl_2$ was added to reduce enzymatic activity that could contribute to further volatile changes following tissue maceration and subsequent storage at −80 °C (Buttery and Ling 1993).

Gas Chromatography (GC)

Tomato volatile compounds were identified and quantified by GC using the headspace analysis technique described in Baldwin and others 1991. Each sample was thawed under running tap water and a 2-mL sample was withdrawn, placed inside a 6-mL vial and sealed with a crimp-top and Teflon-silicone septum. Vials were rapidly heated and incubated at 80 °C for 15 min before injection using a Perkin Elmer HS-6 headspace-sampler (Perkin Elmer, Norwalk, Conn., U.S.A.). The analysis was carried out using a Perkin Elmer Model 8500 gas chromatograph equipped with a 0.53 mm x 30 m polar stabilwax capillary column (1.0- m film thickness, Restek Corp., Bellefonte, Pa., U.S.A.) and a flame ionization detector. Initial column temperature was held at 40 °C for 6 min, then raised to 180 °C at a rate of 6 °C/min where it was held constant for an additional 8 min.

Previous studies (Baldwin and others 1991; McDonald and others 1996) evaluated 16 important tomato aroma volatile compounds (acetaldehyde, acetone, methanol, ethanol, 1-penten-3-one, hexanal, *cis*-3-hexenal, 2+3-methylbutanol, *trans*-2-hexenal, *trans*-2-heptenal, 6-methyl-5-hepten-2-one, *cis*-3-hexenol, 1-nitro-2-phenylethane, geranylacetone, 2-isobutylthiazole, and β-ionone) based on their positive log-odor values in aqueous solutions as determined by Buttery and others (1988) and Tandon (1998). The GC peaks for the aroma volatile compounds of interest were quantified in μL/L using standard curves as determined by enrichment of bland tomato homogenate, obtained after roto-evaporating tomato volatiles for 4 h at 50 °C, then, mixed with known concentrations of authentic volatile compound standards for GC analysis (Baldwin and others 1991).

Electronic Nose Analysis (EN)

Approximately 20 g from each frozen tomato homogenate sample was placed inside 113-mL plastic cups, lidded and thawed in a 25 °C water bath. Immediately upon thawing, the lid was removed and the sample cup placed inside the glass vessel of an electronic nose (e-NOSE 4000, Neotronics Scientific, Flowery Branch, Ga., U.S.A.). EN analysis and sensor data acquisition was controlled by personal computer (Intel 486 SX processor at 66 MHz speed) with software developed by the EN manufacturer. EN sampling began with a 2 min purge of the glass vessel using compressed air. Next, the sampling head, containing 12 polymer sensors (manufacturer ID numbers: T301, T298, T297, T283, T278, T264, T263, T262, T261, T260, T259, and T258), was purged with compressed air for 4 min to eliminate any volatile compounds in contact with the polymer sensors. While the sensor head was being purged, the headspace inside the sealed, sampling vessel equilibrated with the volatiles produced by the tomato sample. Finally, the sensor head was lowered into the sampling vessel and exposed to the tomato volatiles for 4 min. Polymer sensor output, relative humidity and temperature measurements inside the sensor head were recorded during analysis. The total EN analysis time was 10 min per sample.

Compositional Analyses

Tomato homogenate samples from each of the temperature treatments were centrifuged at 18,000 × g_n and 5 °C. The resulting supernatant was filtered through cheesecloth, and stored inside scintillation vials at −20 °C for later analysis. Titratable acidity, expressed as % citric acid, was determined by titrating 1.5 g of tomato supernatant to pH 8.2 with a 0.1 N NaOH solution using an automatic titrimeter (Fisher Scientific, Pittsburgh, Pa., U.S.A.). Soluble solids, expressed as °Brix, was measured using a tabletop digital refractometer (Abbe Mark II, Reichart-Jung, Buffalo, N.Y., U.S.A.) and pH measurements were conducted using a digital pH-meter (Corning model 140).

Tomato fruit lycopene content was determined using a colorimetric method adapted from Umiel and Gabelman (1971). Four 10 g samples of tomato homogenate were each mixed with 30 mL of acetone in 100-mL glass vials covered with aluminum paper for 60 sec using a Polytron. After mixing, the samples were vacuum filtered (Whatman # 4 filter paper) into 500 mL sidearm Erlenmeyer flasks containing 45 mL of hexane. The hexane-lycopene phase was separated from the acetone through a series of deionized water washes using separatory funnels. Absorbance was determined at 503 nm using a spectrophotometer (Beckman DU-20, Irvine, Calif., U.S.A.). Lycopene concentrations were determined using standard curve derived from pure lycopene standards.

Individual sugar analysis (glucose and fructose) was performed using an adaptation of the high performance liquid chromatography (HPLC) method described by Baldwin and others (1991). Approximately 20 g tomato homogenate were extracted using 35 mL 80% ethanol/deionized water solution. The homogenate/ethanol mixture was boiled for 15 min, then cooled prior to filtration (Whatman # 4 filter paper). The filtered solution was brought to 50-mL with 80% ethanol in a volumetric flask. Ten mL filtered solution were then passed through a C-18 Sep-pak (Waters/Millipore, Milford, Mass., U.S.A.), followed by a 0.45 μm Millipore filter. Sugars were analyzed using HPLC refractive index detector (Perkin Elmer, Norwalk, Conn., U.S.A.) equipped with a Waters Sugar Pak column and a 10^{-4} M ethylenediaminetetraacetic acid disodium calcium salt (CaEDTA) mobile phase (0.5 mL min^{-1} flow rate at 90 °C). To better represent the sweetening power of individual hexoses, glucose and fructose concentrations were converted to sucrose equivalents (Koehler and Kays 1991) by multiplying their concentrations by 0.74 and 1.73, respectively.

Statistical Analysis

Descriptive sensory panel scores for the flavor descriptors were analyzed as complete block design with panelists as blocks and storage temperatures as treatments using GLM procedure of SAS v 6.12 (SAS Institute, Cary, N.C., U.S.A.). GC aroma volatile compound concentrations, titratable acidity, pH, soluble solids, glucose, and fructose concentrations and sucrose equivalents were analyzed by MANOVA and Duncan's Multiple Range test (∝ = 0.05) was used for mean separations with SAS. Electronic nose sensor outputs were analyzed using standard multivariate discriminant (MVDA). Calculation of Mahalanobis distances (MD) and canonical plot analysis were carried out using STATISTICA v 4.5 (Statsoft Corp., Tulsa, Okla., U.S.A.). Canonical plot analysis developed a series of canonical functions employing EN sensor outputs as variables. Canonical functions 1 and 2 for every individual plot helped to graphically explain the variations in EN sensor outputs between samples from different storage treatments. Relationships between instrumental and sensory parameters were explored through the use of correlation matrices (PROC CORR) and stepwise regressions (PROC STEPWISE) using SAS.

Results

'BHN-189' Tomatoes

After only 2 d storage, tomato flavor was significantly affected as noted by sensory panels and corroborated by instrumental measurements. Panelists rated 'BHN-189' tomatoes stored at 5 °, 10 °, and 12.5 °C significantly lower ($P < 0.05$) in ripe aroma, tomato flavor, and significantly higher in off-flavors (5 °C stored fruit), when compared to fruit stored at 20 °C (Figure 1). GC aroma volatile profiles showed that 2 of the 16 compounds quantified had significant concentration differences between temperature treatments. Notably, tomatoes stored at 5 °C had the highest concentrations of *cis*-3-hexenal and 2-isobutylthiazole (Table 1). Additively, the total concentration of important aldehydes and ketones were significantly different among fruit stored at different temperatures. Statistical analysis from EN sensor outputs using canonical plots separated the temperature treatments into 4 clusters, of which only the 20 °C cluster was distinctively separated from the rest (Figure 2a). Canonical plot analysis employed two linear functions (canonical function 1 and 2) to explain the variation in outputs from the 12 EN sensors. The Mahalanobis distances (MD) (the distance between the centroids of

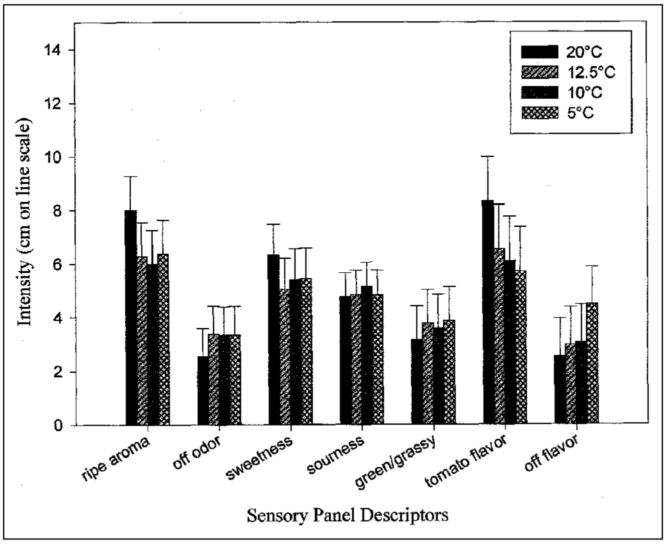

Figure 1—Sensory panel descriptor ratings for table-ripe 'BHN-189' tomatoes stored for 2 d at 4 different temperatures. Significant differences (∝ = 0.05) within temperature treatments for each descriptor were determined using Duncan's Multiple Range Test. Deviation bars represent Duncan's critical ranges for mean separations at the 5% level.

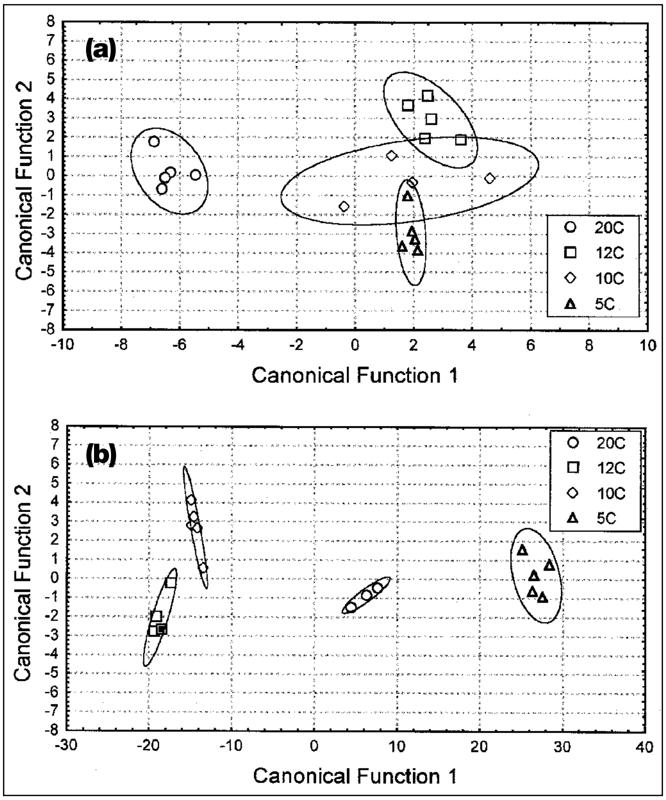

Figure 2ab—Canonical plot analysis of electronic nose sensor outputs for ripe 'BHN-189' tomatoes after: a) 2 d of storage, b) 8 d of storage. Ellipses around clusters represent 95% confidence bands. Increasing distance between clusters relates to greater dissimilarity between samples.

two classification clusters adjusted for probability) ranged between 5.73 and 10.50 units. Greater MD values represent greater degree of dissimilarity between tomato samples. MVDA classified tomato samples according to their temperature treatment with 96% to 100% accuracy based on volatile differences detected by EN after only two d of storage at different temperatures.

Fruit held for 2 d at 12.5 ° or 20 °C were significantly lower in pH when compared to those stored at 5 ° or 10 °C (Table 2). Soluble solids content and titratable acidity showed no significant differences between temperature treatments after two d of storage. Glucose levels were significantly higher in samples stored at 5 °C when compared to those stored at 12.5 °C or 20 °C. Fructose levels and sucrose equivalents were significantly higher in samples stored at 5 °C and 10 °C when compared to those stored at higher temperatures. Sucrose equivalents were highest in fruit stored at 5 °C and 10 °C. Meanwhile, lycopene content was significantly lower in tomato fruit stored at 20 °C.

'BHN-189' tomatoes after 8 d of storage at 5 °C were rated significantly lower in ripe aroma, sweetness and tomato flavor and were perceived more sour when compared to those stored at higher temperatures (Figure 3). GC analysis showed 13 of 16 compounds had significant concentration differences due to storage temperature treatment. Tomatoes stored at 20 °C had the highest concentrations of acetaldehyde, acetone, ethanol, hexanal, 2+3-methybutanol, *trans*-2-hexenal, *trans*-2-heptenal, 6-methyl-5-hepten-2-one, *cis*-3-hexenol, 2-isobutylthiazole, and geranylacetone. Conversely, the concentration of 1-nitro-2-phenylethane was highest in tomatoes stored at 5 °C. It is important to note that tomatoes stored below 10 °C had significantly lower concentrations of *trans*-2-hexenal, *cis*-3-hexenol and geranylacetone compared to those stored at or above 12.5 °C (Table 1). Such ester and ketone volatiles are considered important in imparting fruity flavors associated with ripeness (Petro-Turza 1987). EN analysis separated the temperature treatments into distinct clusters with Mahalanobis distances between them ranging between 8.8 and 18.58 units, greater MD's relating to greater dissimilarities between clusters (Figure 2b). MVDA cross-validation of tomato classification clusters from the different treatments utilizing canonical functions had 100% accuracy after 8 d of storage. High degree of accuracy would imply the capability of MVDA analysis to predict storage treatments of unknown tomato samples based on their EN sensor outputs. EN sensor accuracy was probably due to the greater magnitude of volatile compound changes after prolonged storage at low temperatures.

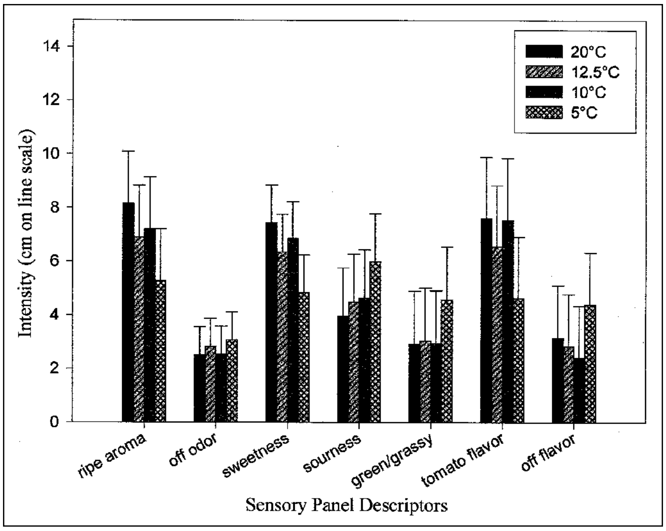

Figure 3—Sensory panel descriptor ratings for ripe 'BHN-189' tomatoes stored for 8 d at 4 different temperatures. Significant differences (∝ = 0.05) within temperature treatments for each descriptor were determined using Duncan's Multiple Range Test. Deviation bars represent Duncan's critical ranges for mean separations at the 5% level.

Table 1—Aroma volatile compound concentrations for table-ripe 'BHN-189' tomatoes stored for 2 and 4 d at 4 different temperatures (5 °, 10 °, 12.5 °, and 20 °C).

	Tomato Aroma Volatile Concentrations[z]																
Storage Temperature	Acetaldehyde	Acetone	Methanol	Ethanol	1-Penten-3-one	Hexanal	*Cis*-3-hexenal	2+3-Methylbutanol	*Trans*-2-hexenal	*Trans*-2-heptenal	6-Methyl-5-hepten-2-one	*Cis*-3-hexenol	2-Isobutylthiazole	1-Nitro-2-phenylethane	Geranylacetone	β-ionone	Total[y]
	'BHN-189' Tomatoes after 2 d of Storage																
20 °C	23.97 a	0.45 a	263.85 ^{a}	27.05 a	0.08 a	4.17 a	1.14 ab	1.14 a	3.00 a	0.02 a	0.85 a	1.03 a	0.06 bc	0.06 a	3.18 a	0.14 a	330.18
12.5 °C	21.65 a	0.40 a	287.00 a	25.83 a	0.10 a	3.36 a	1.48 a	1.03 a	2.51 a	0.02 a	0.69 a	1.06 a	0.05 c	0.06 a	2.57 a	0.14 a	347.93
10 °C	20.42 a	0.49 a	295.97 a	25.82 a	0.08 a	2.02 a	0.80 b	0.91 a	2.65 a	0.02 a	0.75 a	0.86 a	0.10 b	0.06 a	3.47 a	0.12 a	354.52
5 °C	18.25 a	0.36 a	309.75 a	23.88 a	0.08 a	2.69 a	1.51 a	1.07 a	2.70 a	0.02 a	0.68 a	0.92 a	0.16 a	0.06 a	2.81 a	0.20 a	365.14
	'BHN-189' Tomatoes after 8 d of Storage																
20 °C	19.01 a	0.42 a	241.42 a	19.38 a	0.12 a	8.20 a	2.32 a	0.76 a	4.52 a	0.04 a	1.07 a	0.92 a	0.14 a	0.07 ab	4.72 a	0.16 a	303.25
12.5 °C	13.01 b	0.39 b	252.76 a	15.02 b	0.10 a	6.72 b	4.05 a	0.67 a	4.26 a	0.03 b	0.52 c	0.67 b	0.09 b	0.07 b	3.62 b	0.17 a	302.14
10 °C	11.35 bc	0.33 b	213.27 a	15.46 b	0.06 a	1.60 c	2.55 a	0.51 b	2.68 b	0.02 c	0.85 b	0.47 c	0.06 c	0.07 b	2.55 c	0.16 a	251.97
5 °C	10.03 c	0.34 b	249.86 a	14.16 b	0.06 a	1.90 c	3.64 a	0.64 ab	2.86 b	0.02 c	0.87 b	0.34 c	0.09 b	0.08 a	2.45 c	0.06 b	287.48

[z] Aroma volatile compound concentration means (μL/L) with different letters across rows are significantly different at the 5% level according to Duncan's Multiple Range Test

[y] Total aroma volatile production represents the sum of the concentrations of the 16 compounds quantified

'BHN-189' tomatoes stored at 5 °C for 8 d had the lowest pH whereas fruit stored at 20 °C the highest pH. No significant differences in titratable acidity were evident between temperature treatments (Table 2). Soluble solids were significantly higher in fruit stored at 10 °C, while lowest in fruit stored at 12.5 °C. Glucose, fructose, and sucrose equivalents were highest in tomato samples stored at 12.5 °C. Meanwhile, lycopene content was lowest in tomato fruit stored at 20 °C.

'Solimar' Tomatoes

After 4 d of storage, 'Solimar' tomatoes held at 5 °C were rated significantly lower in ripe aroma, sweetness, tomato flavor, and significantly higher in sourness compared to those stored at higher temperatures (Figure 4). GC analyses showed that 4 of the 16 aroma volatile compounds (hexanal, 2+3-methylbutanol, *trans*-2-heptenal and 2-isobutylthiazole) had significantly lower concentrations in samples stored at 5 °C when compared to those stored at 20 °C or 12.5 °C (Table 3). Tomatoes stored below 12.5 °C exhibited lower levels of 2-isobutylthiazole compared to those stored at 20 °C. EN analysis separated the temperature treatments into 4 distinct clusters (Figure 5a). MD values ranged between 3.74 and 12.23 units. Cross validation of the temperature treatments with EN sensor output classification had 83.7% to 100% accuracy.

'Solimar' fruit stored at 5 °C had significantly higher titratable acidity and soluble solids content when compared to rest of temperature treatments (Table 4). No significant differences in pH were found between temperature treatments after 4 d of storage. Glucose levels were significantly lower in samples stored at 10 °C when compared to the other temperature treatments. Meanwhile, fructose content was lowest in samples stored at 20 °C. Sucrose equivalents were significantly lower in tomatoes stored at 10 °C and 20 °C, when compared to those stored at 5 ° or 12.5 °C (Table 4).

Similarly, 'Solimar' tomatoes held at 5 °C for 8 d were still rated significantly lower in ripe tomato aroma and tomato flavor, and significantly higher in sourness, when compared to higher temperatures (Figure 6) as was recorded for 4 d. Conversely, fruit stored at 20 °C were rated higher in sweetness while lower in sourness compared to chilled fruit. GC analysis showed 8 aroma volatile compounds (methanol, 1-penten-3-one, hexanal, 2+3-methylbutanol, *trans*-2-heptenal, 2-isobutylthiazole, 1-nitro-2-phenylethane, and geranylacetone) with significantly different concentrations between the temperature treatments (Table 3). Among these volatile compounds, fruit stored at 12.5 ° or 20 °C produced the highest levels except for 1-penten-3-one, compared to the other temperature treatments. EN analysis classified the temperature treatments into clusters with a greater separation between treatments (Figure 5b). MD values ranged from 4.79 units to 53.35 units cross validation accuracy ranging from 99.5% to 100%.

Table 2—Results from chemical composition analyses performed on 'BHN-189' after 2 and 8 d of storage at 4 different temperatures.

	Storage Temperatures			
	20 °C	12.5 °C	10 °C	5 °C
Compositional Parameters [Z]	2-d storage			
Titratable acidity (% citric acid)	1.19 a	1.19 a	1.17 a	1.21 a
pH	4.55 b	4.55 b	4.61 a	4.62 a
Lycopene content (μg/g fresh wt.)	27.7 b	33.1 a	31.4 a	37.1 a
Glucose content (% fresh wt.)	1.14 b	1.05 b	1.21 ab	1.24 a
Fructose content (% fresh wt.)	1.27 b	1.18 c	1.42 a	1.38 a
Sucrose equivalents (% fresh wt.)	3.04 b	2.81 c	3.34 a	3.30 a
Soluble solids (°Brix)	3.60 a	3.53 a	3.73 a	3.73 a
	8-d storage			
Titratable acidity (% citric acid)	1.17 a	1.03 a	1.11 a	1.21 a
pH	4.76 a	4.66 c	4.70 b	4.57 d
Lycopene content (μg/g fresh wt.)	19.9 c	27.6 a	28.1 a	23.9 b
Glucose content (% fresh wt.)	0.99 c	1.13 a	1.02 bc	1.06 b
Fructose content (% fresh wt.)	1.20 b	1.30 a	1.17 b	1.24 ab
Sucrose equivalents (% fresh wt.)	2.81 b	3.08 a	2.78 b	2.93 ab
Soluble solids (°Brix)	3.73 b	3.37 d	3.87 a	3.60 c

[Z] Chemical composition parameters between temperature treatments with different letters are significantly different at the 5% level according to Duncan's Multiple Range Test

There were no significant differences in pH or titratable acidity between 'Solimar' tomatoes stored at different temperatures for 8 d. However, soluble solids content was significantly higher in those fruit stored at 5 °C (Table 4). Glucose content was highest in fruit stored at 5 °C; in contrast, these same fruit had the lowest fructose levels. Sucrose equivalents were significantly higher in fruit stored at 5 °C when compared to those stored at higher temperatures. In general, lycopene levels decreased in all 'Solimar' tomatoes after 8 d, regardless storage temperature; however, they attained the lowest level in 5 °C stored fruit (Table 4).

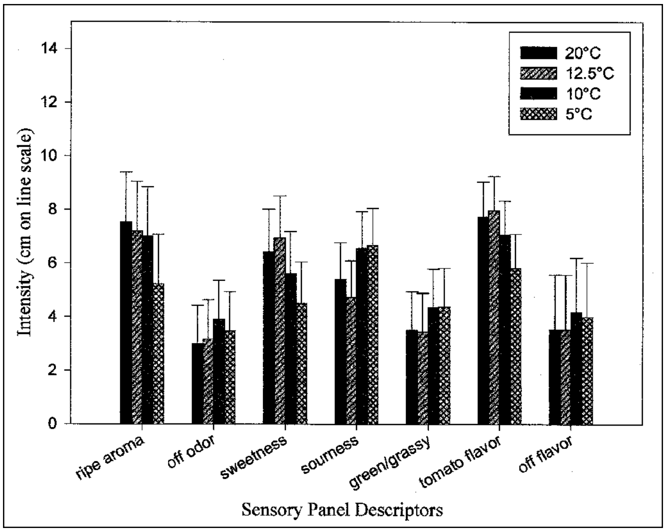

Figure 4. Sensory panel descriptor ratings for ripe 'Solimar' tomatoes stored for 4 d at 4 different temperatures. Significant differences (∝ = 0.05) within temperature treatments for each descriptor were determined using Duncan's Multiple Range Test. Deviation bars represent Duncan's critical ranges for mean separations at the 5% level.

After 12 d, 'Solimar' tomatoes stored at 5 °C were still rated lowest in ripe aroma, sweetness, and tomato flavor. In addition to 5 °C stored fruit, those stored at 10 ° and 12.5 °C became significantly lower in ripe aroma and sweetness (10 °C fruit), and all chilled fruit were significantly higher in green/grassy flavor and sourness compared to those held constantly at 20 °C (Figure 7). GC analysis of aroma volatile compounds identified 13 out of the 16 compounds quantified (acetaldehyde, methanol, ethanol, hexanal, *cis*-3-hexenal, 2+3-methylbutanol, *trans*-2-hexenal, *trans*-2-heptenal, 6-methyl-5-hepten-2-one, *cis*-3-hexanol, 2-isobutylthiazole, 1-nitro-2-phenylethane, and β-ionone) with significant concentration changes as result of the prolonged exposure to the different temperature treatments (Table 3). As in the shorter storage periods, the levels of hexanal, 1-nitro-2-phenylethane and β-ionone were highest in fruit stored at 20 °C.

EN analysis classified 'Solimar' tomatoes stored for 12 d with a greater degree of separation than those stored for either 4 or 8 d (Figure 5c). MD values ranged between 52.47 units and 154.79 units, and cross validation accuracy based on EN sensor outputs was 100% in all cases. Greater separation between classification clusters in Figure 5c made it appear as if only 1 to 2 samples per treatment were analyzed. However, the overlapping of samples within each storage treatment (due to great similarity) was the reason for not being able to clearly show all 5 samples or their 95% confidence ellipses. Tomatoes stored below 10 °C had higher titratable acidity and those stored at 12.5 °C higher pH and soluble solids content compared to fruit from other treatments (Table 4). Meanwhile glucose, fructose, sucrose equivalents and soluble solids were highest in tomatoes stored at 5 °C.

Correlation and Stepwise Regression Analyses

Individual aroma volatile compound concentrations and chemical composition parameters for both tomato cultivars showed significant correlations to sensory ratings. Ripe tomato pH was negatively correlated to off-odor, sourness and green/grassy sensory ratings (r = −0.54, −0.64, and −0.55, respectively), while, positively correlated to sweetness ratings (r = 0.53) (Table 5). Soluble solids content and sucrose equivalents were positively correlated to off-odor (r = 0.48 and 0.49), sourness (r = 0.58 and 0.54), and off-flavor (r = 0.49 and 0.62) sensory ratings, respectively. Titratable acidity was negatively correlated to sweetness ratings (r = −0.48) while, positively correlated to sourness, off-odor and off-flavor sensory ratings (r = 0.66, 0.53 and 0.55, respectively). Concentrations of hexanal, *trans*-2-heptenal, geranylacetone, and β-ionone were positively correlated to ripe aroma ratings (r = 0.68, 0.51, 0.56, and 0.56, respectively). Meanwhile, concentrations of acetaldehyde, acetone, and methanol were positively correlated to off-odor ratings (r = 0.53, 0.59 and 0.58, respectively). Sensory ratings for sweetness were positively correlated to the concentrations of hexanal, *trans*-2-heptenal, 6-methyl-5-hepten-2-one, and geranylacetone (r = 0.59, 0.70, 0.49,

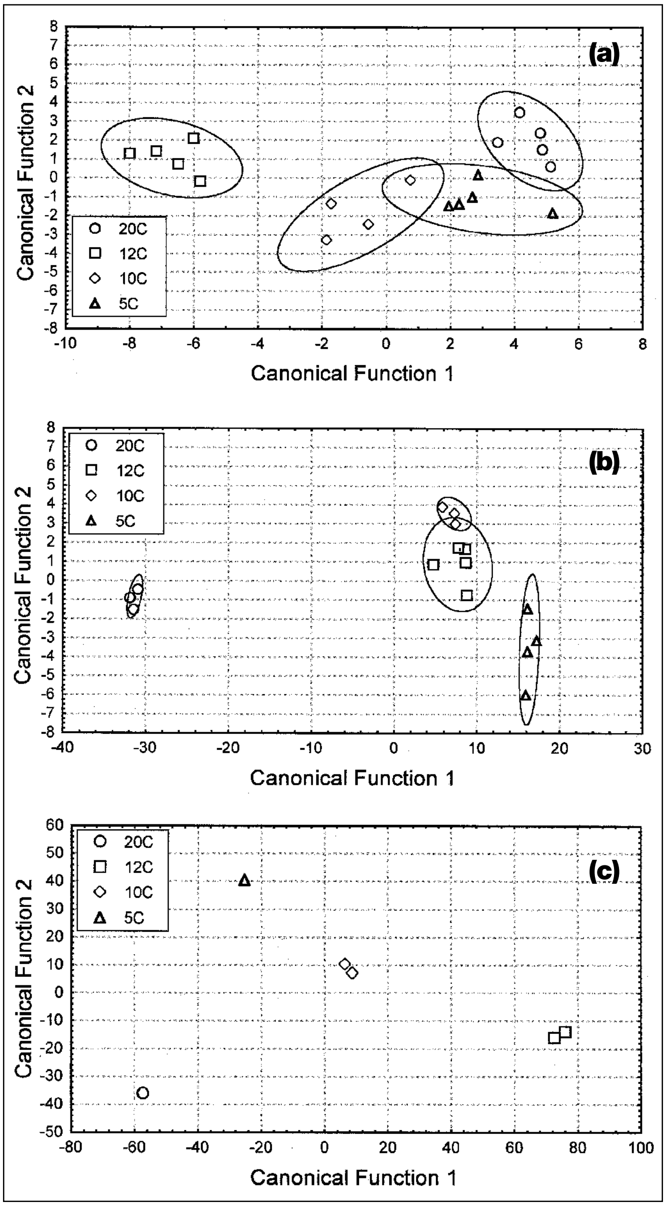

Figure 5abc—Canonical plot analysis of electronic nose sensor outputs for ripe 'Solimar' tomatoes after: a) 4 d of storage, b) 8 d of storage, and c) 12 d of storage. Ellipses around clusters represent 95% confidence bands. Increasing distance between clusters relates to greater dissimilarity between samples.

Table 3—Aroma volatile compound concentrations for table-ripe 'Solimar' tomatoes stored for 4, 8 and 12 d at 4 different temperatures (5 °, 10 °, 12.5 °, and 20 °C).

	Tomato Aroma Volatile Concentrations[z]																
Storage Temperature	Acetaldehyde	Acetone	Methanol	Ethanol	1-Penten-3-one	Hexanal	*Cis*-3-hexenal	2+3-Methylbutanol	*Trans*-2-hexenal	*Trans*-2-heptenal	6-Methyl-5-hepten-2-one	*Cis*-3-hexenol	2-Isobutylthiazole	1-Nitro-2-phenylethane	Geranylacetone	β-ionone	Total[y]
	'Solimar' Tomatoes after 4 d of Storage																
20 °C	28.84 a	0.41 a	245.55 a	21.18 a	0.10 a	4.19 a	1.50 a	0.53 b	3.16 a	0.03 a	0.88 a	1.03 a	0.36 a	0.07 a	3.68 a	0.16 a	311.67
12.5 °C	27.82 a	0.38 a	327.82 a	20.46 a	0.10 a	3.83 ab	1.75 a	1.19 a	3.25 a	0.025 ab	0.70 a	1.02 a	0.20 b	0.08 a	3.49 a	0.17 a	392.30
10 °C	24.52 a	0.51 a	309.26 a	25.79 a	0.09 a	3.67 ab	1.56 a	0.79 b	3.37 a	0.02 b	0.69 a	0.90 a	0.19 b	0.08 a	3.47 a	0.15 a	374.76
5 °C	32.14 a	0.37 a	312.50 a	23.16 a	0.10 a	2.89 b	1.38 a	0.48 b	3.34 a	0.02 b	0.64 a	0.99 a	0.21 b	0.07 a	3.29 a	0.12 a	381.71
	'Solimar' Tomatoes after 8 d of Storage																
20 °C	19.77 a	0.42 a	251.57 c	20.45 a	0.11 ab	7.81 a	1.60 a	0.57 bc	3.33 a	0.03 a	0.82 a	0.83 a	0.36 a	0.076 ab	4.06 a	0.15 a	311.82
12.5 °C	15.88 a	0.31 a	323.88 a	19.28 a	0.10 ab	5.39 ab	2.88 a	1.21 a	3.84 a	0.02 b	0.63 a	0.83 a	0.19 b	0.081 a	3.07 b	0.19 a	377.59
10 °C	18.28 a	0.30 a	277.08 bc	24.88 a	0.09 b	3.97 b	1.64 a	0.85 b	4.51 a	0.02 b	0.61 a	0.69 a	0.18 b	0.078 ab	2.12 c	Nd[x]	335.29
5 °C	30.13 a	0.61 a	303.26 ab	22.68 a	0.13 a	2.72 b	1.33 a	0.42 c	3.29 a	0.02 b	0.59 a	0.86 a	0.19 b	0.064 b	2.10 c	0.11 a	368.51
	'Solimar' Tomatoes after 12 d of Storage																
20 °C	15.91 a	0.37 a	266.54 b	17.96 b	0.13 a	8.45 a	1.71 a	0.69 b	3.38 b	0.03 a	0.87 b	0.83 b	0.24 b	0.07 b	3.37 a	0.14 a	320.67
12.5 °C	22.76 ab	0.43 a	324.76 a	26.36 ab	0.11 a	6.28 b	2.13 a	1.30 a	4.38 a	0.03 a	1.05 a	1.22 a	0.30 a	0.08 a	3.04 ab	0.05 b	394.28
10 °C	26.76 a	0.50 a	342.52 a	35.36 a	0.11 a	2.94 c	1.10 b	1.23 a	3.90 ab	0.02 b	0.84 b	1.27 a	0.24 b	0.08 a	2.54 b	0.10 ab	419.51
5 °C	16.58 b	0.34 a	264.87 b	23.08 b	0.08 a	0.92 d	0.81 b	0.33 c	2.29 c	0.02 b	0.58 b	0.80 b	0.13 c	0.08 a	2.63 b	0.08 ab	313.62

[z] Aroma volatile compound concentration means (μL/L) with different letters across rows are significantly different at the 5% level according to Duncan's Multiple Range Test.
[y] Total aroma volatile production represents the sum of the concentrations of the 16 compounds quantified.
[x] Aroma compound concentrations not detected.

and 0.66, respectively), while negatively correlated to methanol concentrations (r = −0.47). Conversely, sourness ratings were negatively correlated to the concentrations of hexanal, *trans*-2-heptenal, geranylacetone, and β-ionone (r = −0.51, −0.57, −0.54, and −0.53, respectively), while positively correlated to methanol concentrations (r = 0.50). Hexanal and geranylacetone concentrations were positively correlated to tomato flavor ratings (r = 0.46 and 0.53), while 1-nitro-2-phenylethane concentrations were positively correlated to green/grassy ratings (r = 0.47).

Stepwise regression analyses determined that ripe aroma ratings were influenced by hexanal, β-ionone, methanol, 2+3-methylbutanol, *cis*-2-hexenal, and soluble solids content, meanwhile, off-odor ratings were influenced by acetone concentrations and pH values (data not shown). Sweetness ratings were described by *trans*-2-heptenal, 1-penten-3-one, and β-ionone concentrations while, sourness ratings were influenced by titratable acidity, β-ionone, hexanal, and 1-nitro-2-phenylethane concentrations. Green/grassy ratings were described in part by the concentrations of methanol and β-ionone, while, tomato flavor ratings by geranylacetone concentrations. Off-flavor sensory ratings were influenced by sucrose equivalents and 1-nitro-2-phenylethane concentrations.

Table 4—Results from chemical composition analyses for table-ripe 'Solimar' tomatoes stored for 4, 8, and 12 d of storage at 4 different temperatures.

	Storage Temperatures			
	20 °C	12.5 °C	10 °C	5 °C
Compositional Parameters ^{Z}	4-d storage			
Titratable acidity (% citric acid)	1.22 c	1.30 bc	1.33 b	1.46 a
pH	4.54 a	4.51 a	4.52 a	4.52 a
Lycopene content (g/g fresh wt.)	23.2 b	16.3 c	34.9 a	22.2 b
Glucose content (% fresh wt.)	1.82 a	1.82 a	1.63 b	1.98 a
Fructose content (% fresh wt.)	1.19 c	1.36 a	1.27 b	1.39 a
Sucrose equivalents (% fresh wt.)	3.41 b	3.71 a	3.41 b	3.86 a
Soluble solids (Brix)	3.87 c	4.40 b	4.13 b	4.70 a
	8-d storage			
Titratable acidity (% citric acid)	1.36 a	1.33 a	1.33 a	1.40 a
pH	4.52 a	4.50 a	4.51 a	4.49 a
Lycopene content (g/g fresh wt.)	21.0 a	20.8 a	23.1 a	17.5 b
Glucose content (% fresh wt.)	1.36 b	1.47 b	1.36 b	1.80 a
Fructose content (% fresh wt.)	1.65 ab	1.72 a	1.69 a	1.57 b
Sucrose equivalents (% fresh wt.)	3.86 b	4.06 b	3.93 b	4.78 a
Soluble solids (Brix)	4.30 b	4.30 b	4.10 b	4.63 a
	12-d storage			
Titratable acidity (% citric acid)	1.15 bc	1.11 b	1.42 a	1.28 ab
pH	4.48 b	4.52 a	4.46 c	4.49 b
Lycopene content (g/g fresh wt.)	15.9 a	20.4 a	20.3 a	16.0 a
Glucose content (% fresh wt.)	0.83 c	1.04 b	1.07 b	1.37 a
Fructose content (% fresh wt.)	1.24 c	1.26 c	1.35 b	1.67 a
Sucrose equivalents (% fresh wt.)	2.76c	2.95 bc	3.13 b	3.91 a
Soluble solids (Brix)	3.60 c	3.67 c	4.43 b	4.00 a

^{Z}Chemical composition parameters between temperature treatments with different letters are significantly different at the 5% level according to Duncan's Multiple range Test.

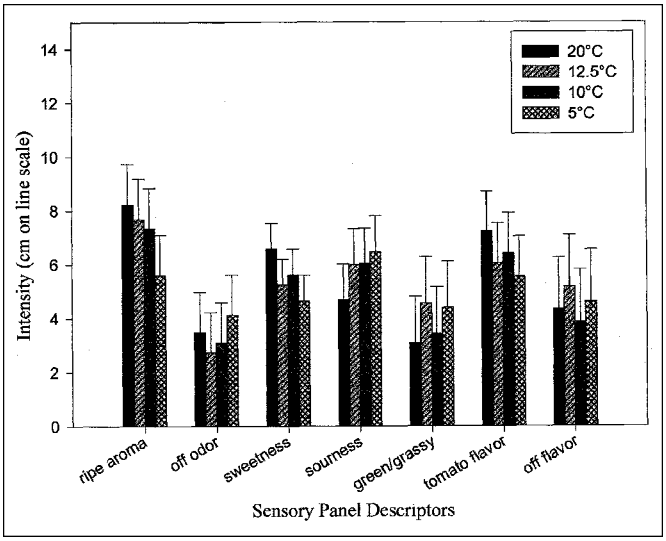

Figure 6—Sensory panel descriptor ratings for ripe 'Solimar' tomatoes stored for 8 d at 4 different temperatures. Significant differences (∝ = 0.05) within temperature treatments for each descriptor were determined using Duncan's Multiple Range Test. Deviation bars represent Duncan's critical ranges for mean separations at the 5% level.

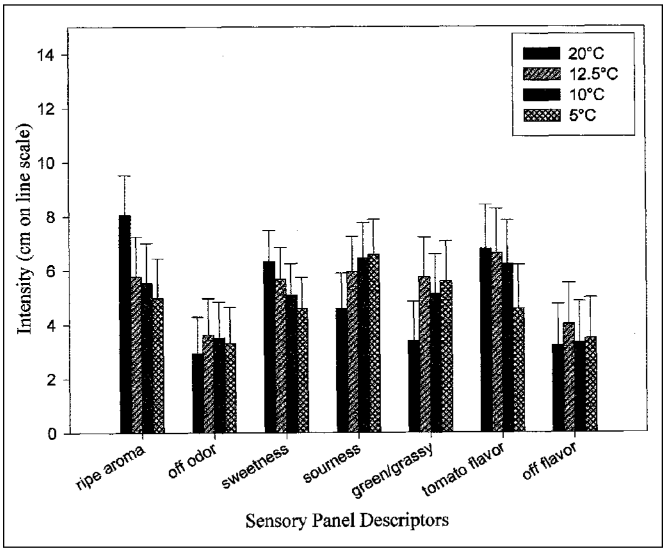

Figure 7—Sensory panel descriptor ratings for ripe 'Solimar' tomatoes stored for 12 d at 4 different temperatures. Significant differences (∝ = 0.05) within temperature treatments for each descriptor were determined using Duncan's Multiple Range Test. Deviation bars represent Duncan's critical ranges for mean separations at the 5% level.

Throughout all EN analyses, there was an apparent relationship between individual EN sensor outputs and the GC aroma volatile compounds quantified in this study. Responses from all 12 EN sensors were negatively correlated to the concentrations of acetaldehyde, methanol, and 2-isobutylthiazole (r = −0.46 to −0.50), while positively correlated to the concentrations of *cis*-3-hexenal (r = 0.49 to 0.50) (Table 6). Surprisingly, concentrations of 1-nitro-2-phenylethane were highly correlated to the responses from all EN sensors (r = 0.97 to 0.98). In addition, EN sensor outputs also showed significant correlations with sensory ratings for sourness and green/grassy flavor, where outputs from all 12 sensors were negatively correlated with sensory ratings (r = −0.45 to −0.58). On the other hand, sensor outputs were highly correlated within themselves (r2 from 0.80 to 0.99), thus supporting the contention of non-specificity among EN sensors.

Discussion

Tomato flavor and aroma were significantly affected by low temperature (< 12.5 °C) for as short as 2-d duration for 'BHN-189' and 4 d for 'Solimar' tomatoes. In general, trained panelists found tomatoes stored at these temperatures to have lower tomato flavor and ripe aroma. Significantly higher off-flavor ratings were found in 'BHN-189' tomatoes after 2 d of storage at 5 °C. In contrast, tomatoes stored at 5 °C during all storage treatment times, and below 20 °C in 'Solimar' fruit after 12 d storage,

Table 5—Correlation coefficients between descriptive sensory panel ratings and compositional parameters from 'BHN-189' and 'Solimar' tomatoes stored at 4 different temperatures for up to 12 d.

Sensory Descriptors	Compositional Parameter	Aroma Volatile Compound
Ripe Aroma		Hexanal r = 0.68 *Trans*-2-heptenal r = 0.51 Geranylacetone r = 0.56 β-ionone r = 0.46
Off-odor	pH r = −0.54 Soluble Solids r = 0.48 Titratable Acidity r = 0.53 Sucrose Equivalents r = 0.49	Acetaldehyde r = 0.53 Acetone r = 0.59 Methanol r = 0.58
Sweetness Hexanal r = 0.59	pH r = 0.53	Methanol r = −0.47 Titratable Acidity r = −0.48 *Trans*-2-heptenal r = 0.70 6-Methyl-5-hepten-2-one r = 0.49 Geranylacetone r = 0.47
Sourness	pH r = −0.64 Soluble Solids r = 0.58 Titratable Acidity r = 0.66 Sucrose Equivalents r = 0.54	Methanol r = 0.50 Hexanal r = −0.51 *Trans*-2-heptenal r = −0.57 Geranylacetone r = −0.54 β-ionone r = −0.53
Green/Grassy	pH r = −0.55	1-nitro-2-phenylethane r = 0.47 β-ionone r = −0.45
Tomato Flavor		Hexanal r = 0.46 Geranylacetone r = 0.53
Off-flavor	Soluble Solids r = 0.49 Titratable Acidity r = 0.55 Sucrose Equivalents r = 0.62	Methanol r = 0.46

Correlation coefficients were significant at the 5% level according to F Test statistics.

Table 6—Correlation coefficients between electronic nose sensor outputs and compositional parameters or sensory panel descriptor ratings from 'BHN-189' and 'Solimar' tomatoes stored at 4 different temperatures for up to 12 d.

EN Sensor	Sensory Descriptor	Aroma Volatile Compound
Type 301	Sourness r = −0.48	Methanol r = −0.46 *Cis*-3-hexenal r = 0.50 1-Nitro-2-phenylethane r = 0.98
Type 298	Sourness r = −0.54 Green/Grassy r = −0.47	Acetaldehyde r = −0.46 Methanol r = −0.49 *Cis*-3-hexenal r = 0.49 1-Nitro-2-phenylethane r = 0.98
Type 297	Sourness r = −0.53	Methanol r = −0.48 Green/Grassy r = −0.46 *Cis*-3-hexenal r = 0.49 1-Nitro-2-phenylethane r = 0.97
Type 283	Sourness r = −0.55 Green/Grassy r = −0.47	Acetaldehyde r = −0.47 Methanol r = −0.49 *Cis*-3-hexenal r = 0.49 1-Nitro-2-phenylethane r = 0.98
Type 278	Sourness r = −0.51	Methanol r = −0.46 Green/Grassy r = −0.45 *Cis*-3-hexenal r = 0.50 1-Nitro-2-phenylethane r = 0.98
Type 264	Sourness r = −0.56 Green/Grassy r = −0.47	Acetaldehyde r = −0.47 Methanol r = −0.48 *Cis*-3-hexenal r = 0.48 1-Nitro-2-phenylethane r = 0.97
Type 263	Sourness r = −0.58 Green/Grassy r = −0.48	Methanol r = −0.49 *Cis*-3-hexenal r = 0.49 1-Nitro-2-phenylethane r = 0.98
Type 262 *Cis*-3-hexenal r = 0.49	Sourness r = −0.52	Methanol r = −0.49 Green/Grassy r = −0.46 1-Nitro-2-phenylethane r = 0.98
Type 261 *Cis*-3-hexenal r = 0.49	Sourness r = −0.52	Methanol r = −0.48 Green/Grassy r = −0.45 1-Nitro-2-phenylethane r = 0.97
Type 260	Sourness r = −0.50 Green/Grassy r = −0.44	Acetaldehyde r = −0.47 Methanol r = −0.49 *Cis*-3-hexenal r = 0.49 1-Nitro-2-phenylethane r = 0.98
Type 259 *Cis*-3-hexenal r = 0.50	Sourness r = −0.54	Methanol r = −0.46 Green/Grassy r = −0.46 1-Nitro-2-phenylethane r = 0.98
Type 258 *Cis*-3-hexenal r = 0.48	Sourness r = −0.54	Methanol r = −0.48 Green/Grassy r = −0.47 1-Nitro-2-phenylethane r = 0.97

Correlation coefficients were significant at the 5% level according to F Test statistics.

were rated significantly lower in sweetness, while significantly higher in sourness. Faster ripening rates and metabolic activity in tomatoes stored at 20 °C were not detrimental to sensory qualities. In addition, fruit firmness was not significantly different between storage temperatures in 'BHN-189' fruit, and 'Solimar' tomatoes stored at 20 °C only became significantly softer than those stored at lower temperatures after 12 d of storage (data not shown).

Chemical composition analyses revealed no consistent pattern that could explain sensory taste descriptor ratings (sweetness and sourness) given to tomatoes stored at different temperatures. Tomatoes held near room temperature (20 °C) were still rated higher in tomato flavor, aroma and sweetness intensity after 12 d of storage, despite having higher respiration rates and carbohydrate reserve consumption than those stored at lower temperatures. Compositional data showed tomatoes stored at 20 °C had significantly lower individual sugars (glucose and fructose) and titratable acidity compared to those stored below 10 °C.

'BHN-189' tomatoes appeared to be more susceptible to low-temperature storage changes than 'Solimar' tomatoes. After 8 d of storage 'BHN-189' fruit had as many aroma volatile compounds showing significant differences as 'Solimar' fruit following 12 d of storage. McDonald and others (1996; 1998) reported that, after 14 d of storage at low temperature (2 °C), tomatoes showed significant changes in the concentrations of numerous important aroma volatile compounds without the presence of other visual CI symptoms. In this study, after only 8 d at 5 °C, 'Solimar' and 'BHN-189' suffered significant concentration changes in all volatile compounds reported by McDonald and others (1996). Concentrations of hexanal, 2+3-methylbutanol, *trans*-2-heptenal, and 2-isobutylthiazole were significantly lower in 'Solimar' and 'BHN-189' fruit stored below 20 °C for all storage periods except for 'BHN-189' after 2 d.

The effects of low temperature storage on tomato aroma volatiles was consistent as shown by considerable reductions in the concentrations of lipid-derived volatiles (hexanal, *cis*-3-hexenal, 1-penten-3-one, *trans*-2-hexenal, *trans*-2-heptenal, and *cis*-3-hexenol) for both 'BHN-189' and 'Solimar' tomatoes at all storage times in this study. The magnitude of volatile concentration changes due to low temperature storage was influenced by cultivar and time of exposure. In 'BHN-189', levels of lipid-derived volatiles were reduced by about 24% and about 50% after 2 and 8 d of storage at or below 10 °C, when compared to those stored at 20 °C. For 'Solimar' tomatoes reductions in lipid-derived volatiles were approximately 9%, 30%, and 36% after 4, 8, and 12 d storage, respectively, in samples stored at or below 10 °C, when compared to those stored at 20 °C. Concentrations of amino acid-derived volatiles (1-nitro-2-phenylethane, 2+3-methylbutanol, and 2-isobutylthiazole) were comparable between temperature treatments for 'BHN-189' tomatoes after 2 d storage and 'Solimar' tomatoes after 4 d storage. However, amino acid-derived volatile concentrations were slightly higher in 'Solimar' samples stored at or below 12.5 °C for 8 and 12 d.

Carotenoid-derived volatiles (acetone, 6-methyl-5-hepten-2-one, geranylacetone, and β-ionone) suffered slight reductions in concentration in samples stored at or below 10 °C for 'BHN-189' after 2 d storage and 'Solimar' after 4 d storage, when compared to those stored at 20 °C (3.4% and 8.5% reductions, respectively). Concentrations of these volatiles were further reduced with longer storage times at or below 10 °C, in 'BHN-189' tomatoes about 42% reductions were documented after 8 d of storage while in 'Solimar' tomatoes concentrations were approximately 45% lower after 8 d storage when compared to those stored at 20 °C.

Fresh-market tomato acceptability is greatly affected by perceived sweetness and sourness (Jones and Scott 1984). Further sensory evidence has indicated that panelists prefer tomatoes with intermediate sourness and relatively high sweetness (Baldwin and others 1998). The effects of sugars on sourness ratings are considerably less important than the effects of acids on sweetness ratings (Petro-Turza 1987). Furthermore, Jones and Scott (1984) showed that above a certain sugar threshold level, the impact of additional sugar concentrations on perceived sweetness may plateau. Such observations helped to understand how tomatoes stored at low temperature (5 °C or 10 °C), with higher sugar levels and higher acidity, would actually be perceived by panelists to be more sour and less sweet. Also, in tomatoes with citric acid contents around 0.80%, Malundo and others (1995) found that increasing sugar concentrations could lead to improved flavor quality, although such benefits were not clearly achievable when acidity levels were higher. In this study, titratable acidity in 'BHN-189' and 'Solimar' decreased with increasing storage times where tomatoes approached 0.80% when stored at 20 °C for 8 to 12 d (0.99% and 0.87%, respectively). Therefore, any changes in fructose concentration during storage, such as those observed in 'Solimar' tomatoes stored at 20 °C, could induce significant changes in sweetness perception.

Previous studies have shown a relationship between volatile compounds and perceived sweetness or sourness (Watada and Aulenbach 1979; Stevens and others 1977). Baldwin and others (1998) reported that *cis*-3-hexenal concentrations correlated negatively with sensory sweetness ratings, while acetone negatively and hexanal positively correlated with tomato sourness ratings. In these tests, significant changes in the concentrations of important aroma volatile compounds in table-ripe tomatoes could partially explain the significant differences in descriptive sensory ratings for the 4 temperature treatments. The number of aroma volatile compounds showing significant differences increased dramatically with increasing storage time. Increased quantitative volatile profile changes with longer chilled storage periods below 20 °C would be explained by a cumulative effect of CI as reported for visual CI symptoms.

Another approach to rate the importance of individual volatile compounds is to contrast the concentration of an individual volatile compound present in a fruit with the concentration threshold for sensory perception, referred to as the odor unit value (OUV) (Guadagni and others 1963; Buttery and others 1988; Tandon 1998). Nonetheless, because of possible interactions with other compounds, odor unit values might not give a clear indication of an individual aroma compound's contribution when in a complex mixture (Baldwin and others 1998). *Cis*-3-hexenal is considered of principal importance due to its high OUV. Odor threshold studies described *cis*-3-hexenal in aqueous solutions as imparting a "fresh green" aroma (Kazeniac and Hall 1970). More relevant to tomato sensory perception, *cis*-3-hexenal was described as having a "tomato/citrus" character when added to bland tomato homogenate (Tandon 1998). Reductions in the concentration of *cis*-3-hexenal after 6 d of storage at 5 °C were reported by Stern and others (1994), and also were obtained in this study for 'Solimar' tomatoes stored at 5 °C. Close relationships between *trans*-2-heptenal concentrations with ripe aroma and sweetness ratings deserve further investigation since there is no published information on this compound's sensory attributes.

Low temperature storage consistently induced changes in 2-isobutylthiazole concentrations, a significant observation since this compound has only been isolated from tomato fruits (Petro-Turza 1987). 2-Isobutylthiazole has been reported to impart "medicinal", "metallic" or "rancid" aroma notes in aqueous solutions with concentrations above 50 μL/L (Kazeniac and Hall 1970), and in recent odor threshold studies with bland tomato homogenate, it contributed a "pungent/bitter" character (Tandon 1998). In this study, significantly higher 2-isobutylthiazole concentrations found in 'BHN-189' tomatoes after 2 d storage suggest that higher off-flavor ratings might be influenced by this volatile compound. Six-methyl-5-hepten-2-one and β-ionone have been reported to impart a "fruity" aroma (Kazeniac and Hall 1970) and "sweet/floral" aroma when added to bland tomato homogenate (Tandon 1998). Both these ketone compounds are thought result from the breakdown of lycopene and other carotenoid pigments (Buttery and Ling 1993). The reduction in lycopene content for tomatoes observed during these tests could affect the production of important ketone volatile compounds.

EN sensor output analysis using multivariate discriminant analysis classified ripe 'BHN-189' tomato samples into distinct clusters by storage temperature following two d of storage. In fact, increasing MD values from the EN analysis concurred with an increasing number of aroma volatile compounds showing significant differences. The increasing number of compounds showing significant concentration differences with longer storage regimes might reflect the events occurring to the remaining 380 + volatile compounds present in the characteristic ripe tomato aroma/flavor. There is considerable debate in relation to the contribution of any specific volatile compound to tomato aroma. Nonetheless, the ability of the EN sensor array to detect an increasing dissimilarity between these samples supports the contention that greater quantitative and qualitative changes occur in the fruit's aroma volatile profile.

This study provides strong evidence that postharvest storage of fresh-market tomatoes at currently recommended temperatures of 10 ° to 12.5 °C could induce significant negative alterations in flavor and aroma prior to the appearance of visual CI symptoms. Trained descriptive sensory panels, GC aroma volatile profiles, and EN sensor outputs distinguished increasing effects of storage temperature as exposure time increased. Furthermore, short-term storage of ripe tomatoes at typical household refrigerator temperatures (3 °C to 5 °C) could be one of the most contributing factors to consumer complaints about inferior tomato flavor.

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