Flavor and Texture of Banana Chips Dried by Combinations of Hot Air, Vacuum, and Microwave Processing

WINNIE W. Y. MUI, TIMOTHY D. DURANCE, AND CHRISTINE H. SCAMAN*

Food, Nutrition, and Health, Faculty of Agricultural Sciences, University of British Columbia,
6650 Northwest Marine Drive, Vancouver, British Columbia, Canada V6T 1Z4

The behavior of 16 volatile compounds of banana during a combination of air-drying (AD) and vacuum microwave-drying (VMD) of banana chips was characterized. Samples were AD to remove 60, 70, 80, or 90% of moisture (wet basis) and then subjected to VMD to achieve a final moisture content of 3% (dry basis). Banana slices were also dehydrated using only AD, VMD, and freeze-drying (FD) for comparison. Samples that underwent more VMD had significantly lower levels of volatile compounds, which is attributed to the decreased formation of an impermeable solute layer on the surface of the chips. High values for water solubility and relative volatility of compounds correlated with losses during VMD; however, additional factors appear to influence the behavior of compounds during VMD processing. The optimal process of 90%AD/10%VMD yielded crisper banana chips with significantly higher volatile levels and sensory ratings than AD chips.

KEYWORDS: Vacuum microwave; dehydration; air-drying; banana chips; flavor volatiles; mechanism; crispness; sensory evaluation

INTRODUCTION

Flavor plays an important role in food acceptability but the volatile compounds that comprise flavor may easily be lost, degraded, or oxidized during processing steps such as dehydration. This can result in a change in the quality, intensity, and balance of the flavor perception. In conventional hot air-drying (AD), high temperatures and long drying times can cause thermal degradation or volatilization of important flavor compounds (*1*, *2*). Although freeze-drying (FD) can be applied to circumvent thermal damage and produce products with good retention of flavor compounds, this technique is costly and time-consuming (*3*).

Vacuum microwave-drying (VMD) offers an alternative way to improve the quality of dehydrated products and potentially retain volatile compounds sensitive to losses through thermal and oxidative degradation. The microwaves supply energy for rapid heat transfer, and the vacuum lowers the boiling point of water in the food material. These conditions allow vaporization of moisture at a lower temperature than occurs at atmospheric pressure, thereby minimizing thermal damage to the food products. Also, the vacuum removes most of the oxygen in the system, diminishing oxidative reactions and preserving flavor and color of the dehydrated products (*4*). VMD has been used successfully for the dehydration of various products, including grapes (*5*), cranberries (*6*), potatoes (*7*), bananas (*8*), shrimp (*9*), and carrots (*10*). The resulting dried products possessed excellent quality in terms of taste, aroma, texture, and appearance.

There is evidence that VMD can result in products with greater retention of volatile compounds as compared to air-dried foods. VMD oregano was found to contain more thymol, a key character impact compound, than material that had been air-dried (*11*). Significantly higher levels of key volatiles were also found in VMD sweet basil as compared to air-dried samples (*12*). For economic and practical purposes, it is often necessary to air-dry the food material prior to VMD. Not all of the factors that influence the retention of volatile compounds during VMD in combination with AD have been determined. Therefore, the effect of various amounts of AD prior to VMD on the retention of volatile components in banana chips was investigated and compared to conventional AD and FD processes. Because textural attributes are critical in acceptance of a snacklike product such as banana chips, the effect of the processes on instrumental textural attributes was also evaluated.

MATERIALS AND METHODS

Raw Materials. Bananas were purchased from a local supermarket and stored at 20 °C until fully ripe, reaching a stage having a yellow color with small brown spots. The bananas were carefully matched according to degree of ripeness. The maturity of the bananas was determined by measuring skin color and starch content (*13*, *14*). The banana samples used had a skin color with Hunterlab L, *a* and *b* values of 52.1 ± 1.8, 8.83 ± 0.59, and 22.6 ± 1.4, respectively, and tissue starch content corresponding to *L* values of 41.3 ± 1.5, *a* values of 4.73 ± 0.44, and *b* values of 14.9 ± 0.9, after iodine staining. Prior to each drying treatment described below, bananas were peeled, sliced to a thickness of 6 mm, and dipped in a solution of 2000 mg/L potassium metabisulfite for 2.5 min. All experiments were performed in triplicate. A 650 g sample of banana slices was dried for each replicate.

* To whom correspondence should be addressed. Tel.: 604-822-1804. Fax: 604-822-3959. E-mail: cscaman@interchange.ubc.ca.

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Preparation of Combined Air-Dried−Vacuum Microwave-Dried Banana Chips. The slices were first air-dried on a Vers-a-belt dryer (Wal-Dor Industries Ltd., New Hamburg, ON, Canada, belt area 0.6 m × 2.0 m) at 70 °C, with an air flow rate of 1.1m³/min and relative humidity of 15 ± 3% to remove 60, 70, 80, and 90% of the initial moisture on a wet weight basis. The time required to remove the moisture in the air dryer was 38, 50, 62, and 80 min, respectively. These partially air-dried banana slices were then transferred to a high-density polyethylene drying drum and vacuum microwave-dried in a 2 kW maximum power vacuum microwave dryer (EnWave Corporation, Vancouver, BC, Canada). The drum was rotated at a rate of 4 rpm. After a vacuum was achieved (6.50 kPa absolute pressure), the partially air-dried banana slices were vacuum microwave-dried at a microwave power of 1.5 kW for approximately 7.5, 6.5, 5.5, and 4.5 min, respectively, to a final moisture content of around 3% on a dry weight basis (db), corresponding to a water activity of 0.266 (60AD/40 VMD), 0.272 (70AD/30 VMD), 0.257 (80AD/20 VMD), and 0.261 (90AD/10 VMD).

Preparation of 100% VMD Banana Chips. The banana slices were positioned on a plastic tray and vacuum microwave-dried at an absolute pressure of 6.50 kPa and a microwave power of 1.5 kW to a final moisture content and water activity of 3% db and 0.291, respectively. Drying was carried out on a tray, rather than in the rotating drum used with the AD/VMD treatments, to prevent fruit pieces from sticking together.

During this drying process, the temperature of the banana slices was measured at 1 min intervals using an infrared thermometer (model 39650-04, Cole Parmer Instruments Co., Chicago, IL). Ten measurements were made at each interval.

Preparation of 100% Air-Dried Banana Chips. The banana slices were air-dried at 70 °C with an air flow rate of 1.1m³/min on a Vers-a-belt dryer for 180 min until the final moisture content of the banana chips reached 3% db, corresponding to a water activity of 0.287.

During the drying process, the weight of the banana slices was recorded to construct a drying curve, and the temperature was measured using an infrared thermometer (model 39650-04, Cole Parmer Instruments Co., Chicago, IL). Ten measurements were taken at each time interval.

Preparation of 100% Freeze-Dried Banana Chips. The banana slices were frozen at −35 °C in a conduction freezing chamber and freeze-dried to a moisture content of approximately 3% db at an absolute pressure of 0.21 kPa with a chamber temperature of 20 °C and a condenser temperature of −55 °C. The water activity of the FD chips was 0.191.

Flavor Analysis of Banana Chips. Banana chips were ground with a mortar and pestle, and 5 g of banana chip powder was made into a slurry with 5 mL of distilled water in a 15 mL Teflon septum-closed vial. A 2 μL aliquot of caproic acid ethyl ester (Sigma Co., St. Louis, MO) in methanol (0.1%, v/v) was added as an internal standard. For fresh banana, 10 g was homogenized and transferred to a vial with the internal standard. The vial containing the banana slurry was placed in a 50 °C water bath. The needle of the solid phase microextraction (SPME) device was then pierced through the septum of the vial, and a Carboxen/PDMS fiber was exposed to the headspace of the slurry for 30 min. The sampling conditions were optimized to yield the maximum peak area of 5 main volatile compounds. All SPME samplings were performed in triplicate.

Gas chromatographic (GC) analysis was performed using a Varian 3700 gas chromatograph (Varian Associates, Inc., Palo Alto, CA) equipped with a flame ionization detector coupled to a Supelcowax-10 fused silica capillary column, 30 m × 0.25 mm i.d., 0.25 μm film thickness, (Supelco Inc., Toronto, ON, Canada). Volatile compounds adsorbed on the SPME fiber were immediately thermally desorbed in the injector port at 250 °C for 5 min in a splitless mode. The column temperature was held at 35 °C for 5 min, increased to 120 °C at 3 °C/min, and then to 180 °C at 6 °C/min. The detector port was set at 280 °C. Flow rates of the helium makeup gas and the hydrogen gas were set at 30 mL/min and for air at 60 mL/min. The head pressure of the column was set at 15 psi, and the flow rate of the helium carrier gas was 1.7 mL/min. Data were collected and processed with the JCL

6000 Chromatography Data System for PC (Jones Chromatography, Lakewood, CO).

GC/mass spectrometry (MS) was used to identify banana volatiles. A 5 g sample of freeze-dried banana chip sample was used for SPME sampling as above. The adsorbed volatile components were thermally desorbed using a 0.75 mm i.d. SPME liner (Supelco Inc., Toronto, ON, Canada) in the injection port at 250 °C for 5 min in a splitless mode. The volatile components were then separated using a Supelcowax-10 fused silica capillary column, 60 m × 0.25 mm i.d., 0.25 μm film thickness (Supelco Inc., Toronto, ON, Canada), installed in the Hewlett-Packard 5890−5970 GC/MSD system. The column temperature was held at 35 °C for 5 min, increased to 120 °C at 3 °C/min, and to 180 °C at 6 °C/min. The head pressure of the column was set at 200 kPa, and the flow rate of the helium carrier gas was 24.9 cm³/sec. The MSD was operated in a scan mode from 40 to 400 amu, and the sample rate was at 1.7 scans/sec. The mass spectral identification was obtained with a G1034C MS Chemstation containing a Wiley 138K MS library.

Sensory Evaluation of Banana Chips. Descriptive sensory evaluation was carried out by six trained panelists to determine the effect of drying methods on the aroma and flavor intensity of banana chip samples (*15*). Sensory analysis was performed in triplicate, with one panel session per week and a total of three panel sessions per study. In each session, panelists were asked to evaluate the aroma and flavor intensity of one complete set of banana chip samples. A sensory score sheet with a 15 cm unstructured line scale, each with anchor points at 1.5 cm from each end and at the midpoint, was provided to evaluate each sensory attribute of the chip samples. Panelists were asked to mark a vertical line across the unstructured line at the point that best reflected their evaluation of the intensity of each attribute.

The sensory tests were conducted in the sensory panel room of the Food Science Building at the University of British Columbia. The sensory panels were conducted under red fluorescent light to minimize the effect of the banana chip color on the assessment of the aroma and flavor attributes. During preparation, three banana chips from each of the seven drying treatments were placed in a lid-closed small plastic container that was labeled with a random three digit code. During the sensory panel, each panelist received all seven treatment samples at the same time on a paper plate. Panelists were asked to bring the container to their noses, remove the container lid, take three sniffs, and evaluate and record the aroma intensity of the chip samples using the sensory score sheet. Subsequently, the panelists were asked to take a bite and chew the samples at least five times in the mouth to assess the flavor and off-flavor attributes. Slices of fully ripe banana were provided as reference standards. Spring water and crackers were provided for the panelists to cleanse their palates between samples.

Instrumental Crispness and Hardness. Banana chips from each replicate of the drying treatments were packed in individual cheesecloth bags and then sealed in an airtight bag. The chips were stored at room temperature for 14 days until the water activity of the samples had equilibrated to 0.25. Textural attributes of the banana chip samples were measured using a texture analyzer TA-XT2 (Stable Micro Systems Ltd., Surrey, England). The test speed was 7.0 mm/s, and the penetration depth of the probe was 12.0 mm. Each chip was centered over a 1 cm hole on a 10 cm × 9 cm metal base. The sample was fractured using a No. 5 flat-ended probe. The slope (g/mm) and peak force (g) were recorded. Fifteen measurements were obtained from each of three replicates, for a total of 45 measurements for each drying treatment.

Statistical Analysis. Minitab statistical software, version 12.1 (State College, PA), was used to perform statistical analyses of the data collected from the experiments. One-way analysis of variance (ANOVA) was performed to examine the effects of drying method on the volatile retention and textural attributes of the banana chips. Differences among treatments were assessed using Tukey's multiple comparison test, and the treatments were considered significantly different when $p \leq 0.05$.

General linear model of ANOVA was performed to examine the effects of drying methods on the aroma and flavor attributes of the banana chip samples. A significant ($p < 0.05$) panelist effect was observed, suggesting that the panelists were using different parts of the scale during the panels. Therefore, the sensory scores were
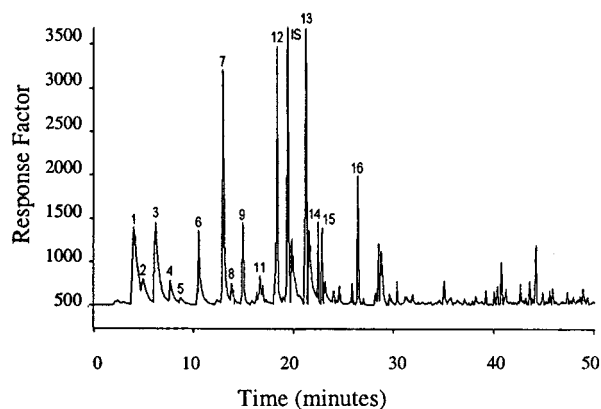
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Figure 1. Typical chromatogram of volatile compounds extracted by SPME of 90% air-dried/10% vacuum microwave-dried banana chips Numbers correspond to compounds identified by GC/MS in **Table 1**. Caproic acid ethyl ester was used as an internal standard.

Z-transformed using the following equation in order to standardize the scores obtained from different panelists (*16*).

$$Z = (x - X)/\text{sd}$$

where *Z* is the transformed score, *x* is the actual sensory scores obtained from a panelist for a specific sensory attribute, and *X* and sd are the mean and the standard deviation of all of the scores from the same panelists for the sensory attribute, respectively. A general linear model of ANOVA was again performed using the *Z*-scores to determine the effects of drying methods on the sensory attributes of the samples. Differences among treatments were assessed using Tukey's multiple comparison test, and the treatments were considered significantly different when $p \leq 0.05$.

RESULTS AND DISCUSSION

A typical chromatogram of volatile compounds extracted from 90AD/10VMD banana chips is shown in **Figure 1**. Sixteen of the volatile compounds extracted from banana chips were tentatively identified by GC/MS (**Table 1**). These 16 volatile compounds were mainly esters of acetates and butanoates and also included alcohol and carbonyl compounds. No previously unreported compound was identified. Several high boiling point volatile compounds were also extracted but were not identified.

Esters accounted for 53.2% of the total volatile compounds extracted from fresh bananas and represented the dominant group of compounds in ripe banana fruit. Acetates accounted for 36.9% of the total volatile compounds, with ethyl acetate (16.3%) being the major component. It was previously reported (*13*) that ethyl acetate was the major component in Valery banana. Isoamyl acetate (9.6%) imparts the characteristic aroma typical of fresh bananas (*13, 17−20*), while butyl acetate (8.1%) and isobutyl acetate (1.4%) are considered to be character impact compounds of banana flavor. Butanoates accounted for 9.3% of the total volatile compounds, including ethyl butanoate (0.3%), isobutyl butanoate (1.5%), and isoamyl butanoate (7.5%). Alcohol and carbonyl compound also contributed to banana flavor and imparted green-woody notes, including 1-butanol (0.7%), 1-hexanol (2.7%), 2-heptanone (0.3%), 3-hydroxy-2-butanone (2.3%), 3-methyl-butanal (6.4%), 2-pentanone (9.7%), and 2-hexenal (20.0%).

Relative amounts of all volatile compounds decreased for all drying treatments in relation to fresh bananas, and drying treatment was found to significantly affect the relative amounts of volatile compounds. Almost all volatile compounds decreased as the extent of VMD increased, with the least total volatile compounds, esters, and acetates found in 100 VMD banana

chips. The 100 FD banana chips retained the most total volatile compounds, esters, and acetates; 90 AD/10 VMD banana chips retained the next highest concentration of these volatile compounds, and 100 AD banana chips retained less of these volatiles than the 90 AD/10 VMD banana chips. Among the acetates, isobutyl acetate, butyl acetate, and isoamyl acetate are considered to be the impact compounds in banana flavor (*13, 17−20*). These volatile compounds followed the same trend of declining concentration with increasing amounts of VMD; again, the least was found in 100 VMD banana chips and the most was found in 100 FD banana chips. 2-Pentanone, while not a key banana character impact compound, was retained in high amounts in the dehydrated chips, accounting for 8.6 (90 AD/ 10 VMD) to 33% (100 VMD) of the total volatiles. The concentration of 2-pentanone tended to increase with increasing amounts of VMD, contrary to the trend of most of the other volatiles. When the amount of 2-pentanone is subtracted from the total volatiles, a consistent trend of decreasing volatile retention with increasing amounts of VMD was observed.

Retention of volatiles during VMD can be influenced by the physical properties of the particular compound as well as the environmental conditions, drying temperature, and the amount of heat input. During microwave heating, the region of maximum temperature, and consequently maximum vapor pressure, is located in the interior of the fruit piece. Therefore, the main driving force for moisture migration is directed toward the fruit surface. Fruit aromas can dissolve into the aqueous phase of the fruit piece. Water absorbs microwave energy selectively; therefore, these compounds can be easily vaporized during VMD (*21, 22*). Furthermore, at the end of VMD, the temperature of the fruit slice is no longer controlled by the boiling point of water at the operating pressure due to the limited amount of moisture available, and the specific heat of the fruit sharply decreases. It was noted that the temperature of the banana slices increased rapidly near the end of the VMD process, reaching temperatures of 72 °C (**Figure 2**). Therefore, some aroma compounds may have undergone thermal degradation at the end of the VMD process.

Retention of volatile compounds during VMD also depends on the characteristics of the compound. Factors such as boiling point, relative volatility in water, molecular weight, and water solubility may be important. In 100 VMD chips, there was either no retention or high losses of a number of compounds including isobutyl acetate, ethyl butanoate, butyl acetate, isoamyl acetate, 1-butanol, isobutyl butanoate, 2-heptanone, 2-hexenal, and isoamyl butanoate. It has been reported that volatile compounds with low molecular weights are microwave unstable and that volatile compounds with high water solubility could easily be vaporized during microwave heating (*22*). An examination of the physical properties of these compounds indicated that the water solubility was most important in determining retention during VMD. Nearly all of the compounds that were poorly retained in the banana chips (except isobutyl butanoate and isoamyl butanoate) exhibited relatively high water solubilities ranging from 0.2 to 6.3 g/100 mL (*23*) and would be expected to exhibit high diffusivity and vaporization during VMD. The water solubility of isobutyl butanoate and isoamyl butanoate is low, reported as "slightly soluble" (*24*), but both of these compounds exhibit high relative volatilities at infinite dilution in water of 1160 and 1260, respectively, (*25*), which may have contributed to their loss during VMD.

The compounds 2-pentanone, 3-methylbutanal, and methyl hexanoate showed relatively high retention in the 100 VMD banana chips, which could be due to their low water solubility.

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Table 1. Effect of Drying Methods on the Relative Concentration of Volatile Compounds of Banana Chips

peak no.	volatile compds (tentative)	60 AD/ 40 VMD	70 AD/ 30 VMD	80 AD/ 20 VMD	90 AD/ 10 VMD	100 AD	100 VMD	100 FD	p^c	fresh banana [e]
1	ethyl acetate	**0.25** d (0.02)	**0.38** cd (0.02)	**0.25** d (0.02)	**0.61** b (0.04)	**0.57** bc (0.06)	**0.38** cd (0.03)	**1.62** a (0.08)	0.000	3.26 (0.20)
2	3-methyl butanal	**0.34** b (0.02)	**0.21** bcd (0.01)	**0.28** bc (0.03)	**0.10** d (0.01)	**0.50** a (0.05)	**0.17** cd (0.004)	**0.52** a (0.06)	0.000	1.29 (0.01)
3	2-pentanone	**1.01** b (0.07)	**1.32** a (0.07)	**0.77** bc (0.05)	**0.55** cd (0.03)	**0.41** d (0.03)	**0.54** cd (0.03)	**1.33** a (0.09)	0.000	1.95 (0.01)
4	isobutyl acetate	**0.025** c (0.002)	**0.085** b (0.005)	**0.097** b (0.006)	**0.10** b (0.01)	**0.024** c (0.001)	**0.000** c	**0.20** a (0.01)	0.000	0.28 (0.01)
5	ethyl butanoate	**0.000** c	**0.000** c	**0.000** c	**0.012** b (0.001)	**0.017** b (0.001)	**0.000** c	**0.036** a (0.003)	0.000	0.054 (0.002)
6	butyl acetate	**0.043** de (0.004)	**0.11** d (0.004)	**0.19** c (0.01)	**0.32** b (0.02)	**0.082** de (0.006)	**0.017** e (0.001)	**0.69** a (0.04)	0.000	1.63 (0.07)
7	isoamyl acetate	**0.15** d (0.01)	**0.39** c (0.03)	**0.45** c (0.02)	**0.69** b (0.04)	**0.23** d (0.01)	**0.016** e (0.001)	**1.20** a (0.06)	0.000	1.92 (0.05)
8	1-butanol	**0.0088** d (0.0009)	**0.019** d (0.002)	**0.024** cd (0.002)	**0.062** b (0.009)	**0.049** bc (0.005)	**0.000** d	**0.11** a (0.01)	0.000	0.15 (0.01)
9	isobutyl butanoate	**0.023** cd (0.003)	**0.028** c (0.003)	**0.032** c (0.003)	**0.13** a (0.01)	**0.076** b (0.006)	**0.000** d	**0.094** b (0.006)	0.000	0.31 (0.04)
10	2-heptanone	**0.000** c	**0.000** c	**0.000** c	**0.000** c	**0.054** a (0.006)	**0.000** c	**0.012** b (0.001)	0.000	0.054 (0.004)
11	methyl hexanoate	**0.14** c (0.01)	**0.19** b (0.01)	**0.096** cd (0.007)	**0.087** d (0.005)	**0.22** ab (0.02)	**0.25** a (0.01)	**0.097** cd (0.007)	0.000	1.4 (0.07)
12	2-hexenal	**0.16** bc (0.01)	**0.32** bc (0.01)	**0.31** bc (0.02)	**0.39** bc (0.03)	**0.54** b (0.03)	**0.006** c (0.0005)	**3.77** a (0.24)	0.000	4.00 (0.14)
13	isoamyl butanoate	**0.11** c (0.01)	**0.39** b (0.04)	**0.66** a (0.07)	**0.83** a (0.06)	**0.29** b (0.02)	**0.031** c (0.001)	**0.30** b (0.02)	0.000	1.51 (0.10)
14	hexyl acetate	**0.067** b (0.004)	**0.13** a (0.01)	**0.10** a (0.01)	**0.10** a (0.01)	**0.036** bc (0.005)	**0.016** c (0.002)	**0.12** a (0.01)	0.000	0.29 (0.02)
15	3-hydroxy-2-butanone	**0.13** bc (0.01)	**0.16** b (0.02)	**0.16** b (0.01)	**0.21** a (0.01)	**0.096** c (0.006)	**0.018** d (0.001)	**0.10** c (0.003)	0.000	0.47 (0.01)
16	1-hexanol	**0.049** de (0.002)	**0.10** cd (0.01)	**0.12** c (0.004)	**0.22** b (0.01)	**0.15** c (0.01)	**0.020** e (0.001)	**0.43** a (0.03)	0.000	0.55 (0.02)
	total acetate	**0.54** d (0.02)	**1.093** c (0.05)	**1.095** c (0.04)	**1.82** b (0.10)	**0.94** c (0.07)	**0.42** d (0.03)	**3.84** a (0.13)	0.000	7.38 (0.26)
	total butanoate	**0.14** c (0.01)	**0.41** b (0.04)	**0.69** a (0.07)	**0.97** a (0.06)	**0.39** b (0.02)	**0.030** c (0.001)	**0.43** b (0.03)	0.000	1.87 (0.10)
	total ester	**0.81** d (0.02)	**1.70** c (0.06)	**1.88** c (0.09)	**2.88** b (0.12)	**1.55** c (0.08)	**0.71** d (0.03)	**4.36** a (0.15)	0.000	10.6 (0.5)
	total of 16 volatile compds	**2.52** d (0.08)	**3.83** bc (0.14)	**3.54** c (0.08)	**4.41** b (0.13)	**3.35** c (0.14)	**1.45** d (0.03)	**10.6** a (0.3)	0.000	19.1 (0.7)
	total volatile compds	**3.41** d (0.11)	**5.16** bc (0.31)	**4.84** c (0.4)	**6.37** b (0.34)	**4.02** cd (0.15)	**1.62** e (0.07)	**13.5** a (0.4)	0.000	20.0 (0.9)

[a] Relative amount = peak area of volatile compound divided by peak area of internal standard. [b] Headspace SPME samplings were performed at 50 °C for 30 min in triplicate on three samples, and measurements are recorded as mean ± standard error mean. [c] Results are considered significantly different at $p \leq 0.050$. [d] Significant differences were determined by Tukey's multiple comparison test. Any two values not followed by the same letter are significantly different at $p \leq 0.050$. [e] The relative amounts of volatile components extracted from fresh banana were indicated here only for comparison. Fresh banana volatile concentrations were obtained using 3.2 times less material (db) as compared to dehydrated banana chips.

However, ethyl acetate was also retained well in these chips, despite having very high water solubility and a low boiling point. Therefore, additional factors appear to be important in determining retention during the vacuum microwave treatment.

It was observed that higher levels of volatile compounds were retained when banana fruits underwent more extensive AD, prior to VMD (**Table 1**). The selective diffusion theory has been proposed to explain the volatile retention during the AD process (*26*). According to this theory, the migration of water and aroma compounds in the drying fruit piece is governed by molecular diffusion. At the beginning of AD, i.e., during the constant rate period of drying, water evaporates freely and volatile compounds are lost rapidly, depending on their relative volatility to water. The aroma loss during AD is mainly controlled by the length of constant rate period (*27*). As AD progresses, water, along with fruit sugars and other solutes, diffuses from the interior to the surface of the fruit piece. When the surface water concentration falls below a critical moisture content, a thin layer of these
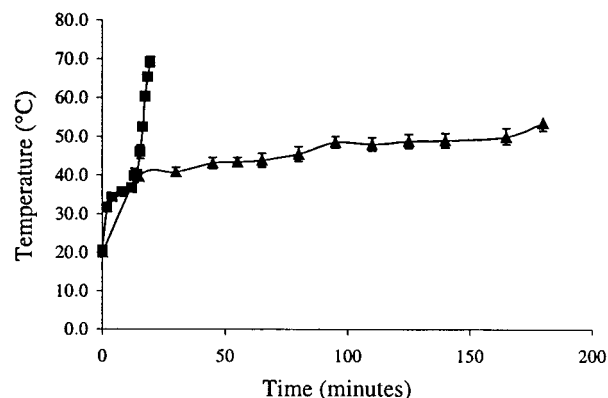

Figure 2. Time–temperature curve of 100% vacuum microwave-dried (■) and 100% air-dried (▲) banana chips. Error bars represent the standard error of the mean (*n* = 10).

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sugars and solutes is formed, thereby covering the drying fruit slice. This thin layer is increasingly impermeable to the diffusing aroma compounds. When the water concentration decreases, the diffusion coefficient of aroma compound decreases much more sharply than that of the remaining water. Hence, the thin layer becomes impermeable to aroma compounds and retains the banana aromas still present in the drying fruit slice. Therefore, as the banana slices underwent more AD and less VMD, more of an impermeable layer was formed on the surface, and more banana aroma compounds were retained in the final product. In support of this theory, a significant positive correlation was noted between the peak force of the force–deformation curve, obtained using the TA-XT2 texture analyzer and the extent of the drying process completed using hot air ($r = 0.91$, $p = 0.01$). The peak force measures the hardness of the surface of the material, and it has been reported as an indicator of the extent of case hardening that has occurred during drying (*28*). Therefore, increasing amounts of moisture loss by diffusion from the interior of the fruit slice during AD correlated with a trend toward more case hardening.

Another factor that may have influenced the retention of volatiles during the AD/VMD processes was the temperature profile of the product. The banana slices reached a maximum of 55 °C during AD (**Figure 2**), well below 70–75 °C that occurred at the end of the VMD; hence, the banana aromas may have been less prone to thermal degradation during the relatively short AD portion of the process. However, prolonged exposure to the hot air for the 100 AD samples was more detrimental to the retention of volatiles than the short time and higher temperature of the vacuum microwave process. The temperature of the 100 AD sample was above 40 °C for about 160 min, while the temperature of the 100 VMD chips was only above 40 °C for about 8 min.

Among the seven drying treatments, FD was found to be the best process for retention of volatile compounds in banana chips. The low processing temperature maintained during FD minimizes the thermal degradation of fruit aromas. The microregion entrapment theory has been used to explain volatile retention in FD (*29*). According to this theory, during the freezing of banana slices, crystallization of water results in the formation of microregions containing highly concentrated solutions of banana aroma compounds and carbohydrates (*30*). As drying progresses, the local moisture content within the microregions decreases, and the molecular association of carbohydrates occurs via hydrogen bonds; thus, the loss of the volatile compounds decreases. As the local moisture content reaches a critical level, the microregion is sealed, and volatile loss ceases. Water loss may still occur, probably because of the small size of water molecules. The volatile retention in the 100 FD banana chips was high for most compounds, except methyl hexanoate, which may be related to the high relative volatility of 650.

ANOVA of *Z*-scores indicated significant differences among seven drying treatments for the sensory attributes of banana aroma, banana flavor, and off-flavor. There was a trend for sensory ratings of aroma and flavor intensity to decrease as the extent of VMD increased, with the lowest rating for the 60 AD/ 40 VMD banana chips (**Figure 3**). For both flavor and aroma, the 100 AD banana chips were perceived as having significantly lower intensity as compared to the 90 AD/10 VMD chips. Also, the 100 AD chips were rated significantly higher for off-flavor than all other treatments.

Correlation coefficients were determined between the sensory attributes and the volatile compounds known to contribute to the characteristic banana aroma (**Table 2**). Sensory attributes
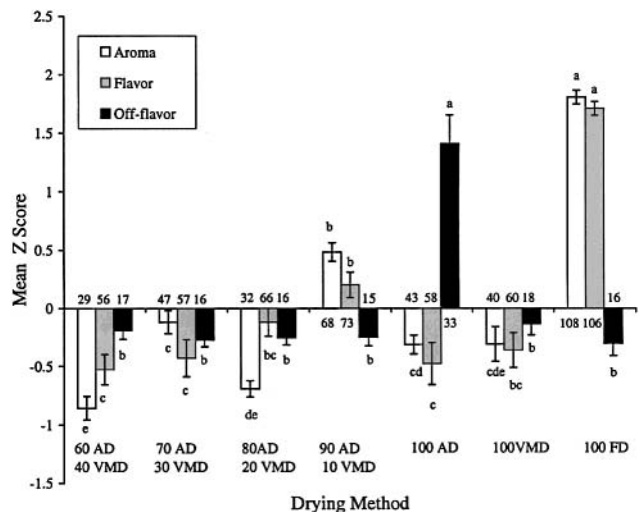

Figure 3. Mean aroma, flavor, and off-flavor *Z*-scores of banana chips prepared with different drying methods. Error bars represent the standard error of the mean ($n = 18$). Any two values not followed by the same letter are significantly different at $p \leq 0.05$. Mean raw aroma scores are also shown for each treatment.

Table 2. Pearson Correlation Coefficients between Sensory Attributes of Aroma, Flavor, and Off-Flavor and Some Volatile Compounds Identified in Freeze-Dried Banana Chips

volatile	aroma[a]	flavor[a]	off-flavor[a]
isobutylacetate	0.825	+0.896	−0.413
	0.022	0.006	0.357
butyl acetate	+0.925	+0.982	−0.298
	0.003	0.000	0.516
isomylacetate	+0.894	+0.934	−0.310
	0.007	0.002	0.499
total acetate	+0.950	+0.975	−0.235
	0.001	0.000	0.611
total ester	+0.920	+0.932	−0.222
	0.003	0.002	0.632
total volatile	+0.909	+0.955	−0.239
	0.005	0.001	0.605

[a] Cell contents: correlation coefficient; *P* value.

of aroma and flavor were highly correlated with the peak areas of the volatile compounds obtained from the gas chromatograms of the banana chips. The sensory aroma and flavor correlated positively with isobutyl acetate, butyl acetate, isoamyl acetate, total acetate, total ester, and total volatile compounds. Sensory off-flavor did not correlate with any of these volatile compounds.

In addition to flavor, textural attributes are critical in determining acceptance of foods; therefore, a puncture test of the chips was carried out. The initial slope of the force–deformation curve is an excellent indicator of crispness of foods (*31*, *32*). The slope, and therefore the crispness, of the AD/ VMD banana chips increased with increasing amounts of VMD and was significantly greater than that of the 100 AD and 100 FD chips (**Figure 4**). Crispness is associated with large voids in the material and expansion (*32*, *33*). The low chamber pressure used during VMD processing results in a high relative internal vapor pressure as a result of microwaves penetrating into the interior of the chips and water being vaporized in situ. This in turn results in an outward force, which expands the fruit structure to create voids, and results in a crisp texture. The structures of potato (*7*) and carrot slices (*10*) were also shown to be expanded and puffed by VMD. The texture of the 100 VMD chips was not evaluated as they were found to be hard, chewy, and not crisp by informal sensory evaluation. Without
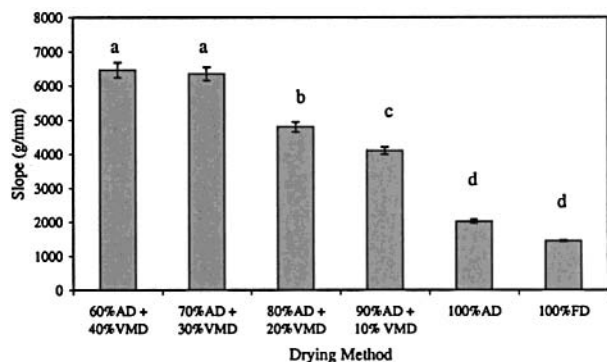
Figure 4. Mean slope (g/mm) of banana chips prepared with different drying treatments. Experiments were performed in triplicate with 15 measurements for each replicate ($n = 45$). Error bars represent the standard error of the mean. Any two values not followed by the same letter are significantly different at $p \leq 0.05$.

some preliminary AD to create a rigid structure, the expansion caused by VMD is not permanent, and the tissue collapses on itself (*31*).

Another factor contributing to the crispness of the chips may have been gelatinization of the starch. The gelatinization temperature range of banana starch was reported to be between 70 and 85 °C (*34*). Because the temperature of the banana slices during VMD reached 70−75 °C, it is likely that at least some of the starch was gelatinized, contributing to the crispness of the chips. The lower maximum temperature recorded for the AD chips of approximately 55 °C was well below the starch gelatinization temperature.

The combination of 90% AD/10% VMD confers benefits over traditional AD of banana chips in terms of flavor retention, textural attributes, and color attributes. While FD banana chips retained more volatile compounds than all AD/VMD processed chips, the textural attributes were not desirable for a snack food product. In addition, FD is a more time-consuming process. Further study is required to determine whether the combination of AD and VMD may be used to enhance the retention of flavor compounds, texture, and color of other dehydrated foods.

ACKNOWLEDGMENT

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