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ABSTRACT

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The objective of this study was to identify and characterize different popped popcorn flake shapes, or polymorphisms, arising from a yellow butterfly popcorn hybrid (YP-213), and then to determine the impact of popcorn flake shape on composition and sensory characteristics. Kernels were popped using a microwave oven and visually sorted into three different polymorphisms depending on whether the appendages were expanded unilaterally, bilaterally, or multilaterally. When popped, 9.0 ± 3.1%, 71.2 ± 5.9%, and 12.3 ± 3.8% of kernels were expanded unilaterally, bilaterally, and multilaterally, respectively, while 7.6 ± 1.4% of kernels remained unpopped. Expansion volumes for unilaterally, bilaterally, and multilaterally expanded polymorphisms were 28.6 ± 3.84, 43.0 ± 0.84, and 53.5 ± 2.5 cm^3/g, respectively. Unilateral popcorn flakes retained the most fat, saturated fat, and sodium, while multilaterally expanded flakes had the highest levels of protein, total carbohydrate, and popcorn-like aromatic pyrazines. Sensory evaluation revealed significant differences among polymorphisms for flavor and texture attributes, with the unilaterally expanded polymorphism receiving the highest overall product liking. These data show that different popcorn flake polymorphisms produced from a single hybrid of popcorn affect sensory and compositional profiles. More research is necessary to elucidate the factors that affect popcorn flake polymorphisms and support development of new varieties or techniques to produce the most desirable microwave popcorn.

Popcorn (*Zea mays* Everta) is a familiar snack food with sizable commercial business in the United States. For instance, annual domestic consumption of popcorn is nearly 4.5×10^8 kg of popped popcorn each year or ≈1.36 kg annually per person, making popcorn a favorite snack food consumed in the United States by volume consumed (The Popcorn Board, online at http://www.popcorn.org).

The most studied and reported quality factor for popcorn is expansion volume. From the outlook of a commercial processor, increased pop expansion produces greater profits because popcorn is purchased by weight yet sold by bulk volume (Lyerly 1942; Song et al 1991). Additionally, high pop expansion volume is correlated with desirable consumer attributes including tender and fluffy texture (Lyerly 1942; Levy 1988) and improved tenderness and palatability (Dofing et al 1991; Ceylan and Karababa 2001). As a result, "lighter and fluffier" popcorn (with higher pop expansion) has the dual benefit of both increasing profits for the manufacturer and increasing enjoyment for the consumer.

While displacement has been used as a method for measuring expansion volume in select cases (Tian et al 2001), the most widespread method for reporting popcorn expansion volume is by measuring bulk density. Other quality factors that are often considered in popcorn include the number or percentage of unpopped kernels, hull dispersion, and the size, shape, color, and texture of the popcorn flake (Ziegler 2001; Quinn Sr. 2005).

Popcorn hybrids are commonly classified as yellow mushroom, white butterfly, or yellow butterfly depending on the type of popcorn flake produced upon popping (Ziegler et al 1984; D'Croz-Mason and Waldred 1990), and specific hybrids are available to produce popcorn flakes of each morphological type (Ziegler 2001). The butterfly-shaped flakes are characterized as having appendages spreading in various directions and are typically preferred for home consumption because they have more tender texture and less prominent hull pieces than mushroom-shaped popcorn (Ziegler 2001). Mushroom-shaped corn is conventionally used for commercial prepopped markets because the popcorn flakes are less susceptible to breakage than the butterfly-shaped popcorn during mixing, coating, and packaging (Eldredge and Thomas 1959).

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Previous researchers have studied the importance of various sensory attributes of popcorn flakes using consumer response evaluations. Matz (1984) and Watson (1988) indicated that consumer acceptability for popcorn flake texture is positively correlated with high pop expansion, freedom from hulls, and formation of butterfly-shaped flakes. Ceyland and Karababa (2001) evaluated the sensory attributes of mushroom and butterfly hybrids including popcorn flake size, uniformity, color, texture, and taste, and found that flake shape was not an independent factor for consideration in the statistical analysis. Park and Maga (2001) also compared sensory attributes from different popcorn hybrids, and they determined that flake polymorphism (limited to mushroom versus butterfly shape) did not significantly affect consumer preference.

Nevertheless, during numerous informal observations, the authors have noted that many consumers appear to hunt for distinct shapes of popped popcorn within a bag or bowl of microwave popcorn. Moreover, visual perceptions of a food product clearly influence the sensorial experience of eating (Hutchins 1977).

Ziegler (2001) illustrated that butterfly-shaped popcorn flakes can assume several distinct polymorphisms; however, no previous studies have sought to characterize the importance or classify differences in flake polymorphism. Accordingly, the purpose of this study was to describe differences in compositional and sensory attributes of different popcorn flake polymorphs obtained from a butterfly-type hybrid, and then to establish relationships between the compositional and sensory measures.

MATERIALS AND METHODS

Materials

Samples of a commercial U.S. yellow butterfly popcorn hybrid (YP-213) were obtained from ConAgra Foods (Omaha, NE). The hybrid used in this study was a composite sample from seed production grown in Nebraska, Iowa, and Ohio in 2009. For compositional analysis, unpopped popcorn kernels were milled using a two-step process of chopping for 20 sec in a Blixer 3 blender (Robot Coupe, Jackson, MS) and then grinding at the highest setting using a Kitchen Mill model 91 (Blentech, Orem, UT). The compositional characteristics of the kernels (Table I) were evaluated using previously published methods: moisture (Official Method 950.46, AOAC International 2010); lipids (Official Method 996.06, AOAC International 2010); protein (Official Approved Method 992.15, AOAC International 2010), with a % nitrogen to protein conversion factor of 5.65 (Park et al 2000);

amylose-to-amylopectin ratio (Zho et al 2008); and minerals Na, K, Ca, Fe, P (Official Method 984.27, AOAC International 2010). Total carbohydrate was measured by difference (100% – [(moisture% + protein% + lipid% + minerals%]). Total sugars were determined by extraction using a 50:50 water and ethanol mixture while shaking in a water bath at 60°C, then quantification by HPLC using an amine phase column (Prevail Carbohydrate ES 5 μm, Grace Discovery Sciences 35101, Deerfield, IL), mobile phase of 75:25, acetonitrile-to-water at 1.0 mL/min, and an evaporative light scattering detector (Alltech 3300). Total starch was determined by enzymatic conversion of starch to glucose using thermostable α-amylase (3,000 U/mL, Megazyme E-BLAAM) and amyloglucosidase (3260 U/mL, Megazyme E-AMGDF), then quantified using the HPLC procedure above for total sugars.

Kernels were tempered to 14% moisture (w/v) content in a controlled cabinet at 21.5°C and 73% relative humidity (rh) for ≈30 days, and then weighed into prefolded, commercially standard, bilayer microwavable paper bags (14.92 × 29.53 cm^2) with an internal capacity of 2,800 cm^3. The bags contained an inlaid aluminum-coated polyester susceptor (13.65 × 16.51 cm^2) positioned on the bottom center of the bag gusset. A slurry of oil, salt, butter flavor, and color was added to the popcorn kernels in each bag, as summarized in the formula shown in Table II. Bags were sealed using heat induction and stored at 21.5°C and 73% rh until used for experimentation (maximum of four months).

TABLE I
Composition of Butterfly Popcorn Hybrid[a]

Analyte	Mean Value/100 g of Sample
Moisture	13.91 ± 0.06 g
Total fat	2.95 ± 0.15 g
Saturated fat	0.53 ± 0.02 g
Fatty acids	
Palmitic (%) C16:0	0.49 ± 0.02 g
Stearic (%) C18:0	0.05 ± 0.00 g
Oleic (%) C18:1	0.61 ± 0.04 g
Linoleic (%) C18:2	1.71 ± 0.09 g
Linolenic (%) C18:3	0.04 ± 0.00 g
All other fatty acids (%)	0.04 ± 0.00 g
Total carbohydrate	73.20 ± 0.15 g
Total starch	70.54 ± 2.84 g
Amylose[b]	11.92 ± 0.35 g
Amylopectin[c]	58.62 ± 0.35 g
Sugars[d]	0.44 ± 0.09 g
Total protein	9.05 ± 0.18 g
Total ash/minerals	0.90 ± 0.07 g
Sodium	Trace
Potassium	232 ± 20 mg
Calcium	4.07 ± 1.66 mg
Iron	2.07 ± 0.22 mg
Phosphorus	237mg ± 21 mg

[a] Analyses run in triplicate.
[b] Amylose determined by method described by Zhu et al (2008).
[c] Amylopectin determined by total starch – amylose.
[d] Only sucrose was detected.

TABLE II
Microwave Popcorn Formulation

Ingredient	Amount Added Per Bag (g)	Total Weight (%)
Popcorn kernels	62.0	67.00
Oil[a]	28.0	30.26
Salt (NaCl)	2.10	2.27
Flavor[b]	0.40	0.43
Color[c]	0.04	0.04
Total	92.54	100.00

[a] Blend of palm oil and palm oil stearine from ADM (84-650-0).
[b] Butter-type flavor from Gilroy Foods (Gen-4981).
[c] Oil suspension of annatto, turmeric, and paprika oleoresin (ATP-1279, Chr. Hansen, Denmark).

Popping and Sorting

All popping tests were completed using a series of seven different GE 1150W microwave ovens (model JE146WF03). The actual power output for ovens was 1,110–1,170 Watts as calculated by the method outlined by Allred-Coyle et al (2000). To standardize popping performance between ovens, 240 mL of water was heated in a ceramic coffee mug for 1.5 min before the first popping of the day. Microwave use was rotated between the seven ovens for popping tests and doors were left open between uses to ensure microwaves cooled down between use and constant oven temperature was maintained for all popping tests performed.

Unfolded bags were placed in the center of microwave with susceptor-side down and popped on high power until the interval between pops slowed to 2–3 sec. The contents were poured into a steel sieve with round-hole, 7.94-mm openings (model 0070, Seedburo, Des Plaines, IL) to remove unpopped kernels, which were counted and weighed. The total popped volume of the sample was measured in a 4-L graduated cylinder and rounded to the nearest 25-mL graduation. Next, the popcorn flakes were visually inspected and segregated into three shapes based on the whether the flake appendages were expanded unilaterally, bilaterally, or multilaterally (Fig. 1).

For each shape, the number of popcorn flakes was counted, weighed, and volumetrically measured five times using a 4-L graduated cylinder and rounded to the nearest 25-mL graduation. The average bulk density of each polymorphous shape was calculated by dividing the pop volume for that shape by the weight of popcorn flakes of that particular shape; the percentage of each polymorphous shape was calculated by dividing the number of flakes obtained of a particular shape by the total number of popped

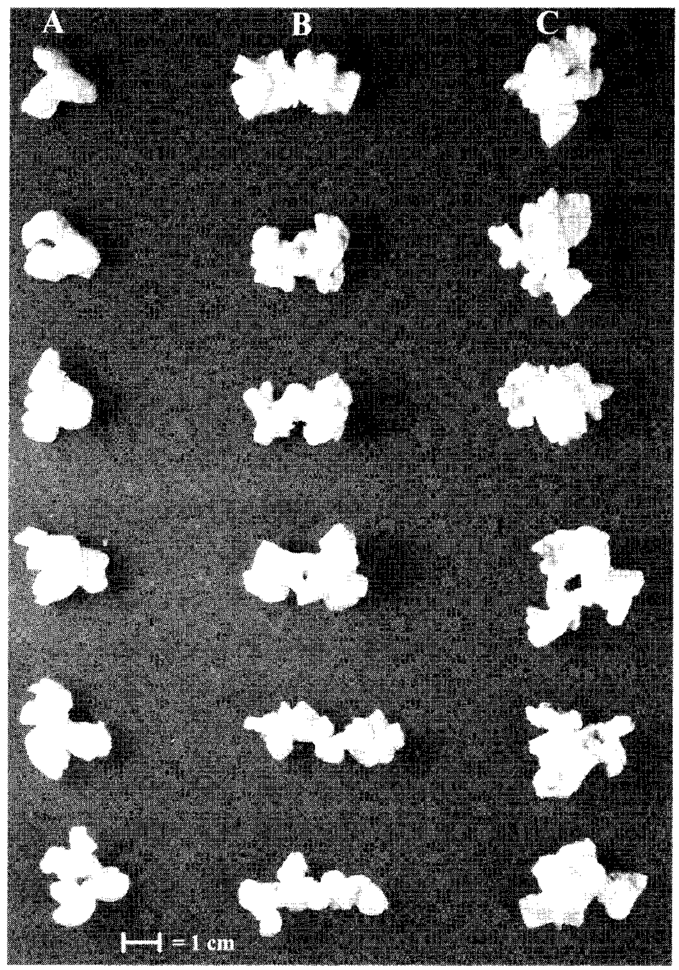

Fig. 1. Popcorn flakes inspected and segregated into three shapes: expanded unilaterally (**A**), bilaterally (**B**), or multilaterally (**C**).

and unpopped kernels; the percent unpopped kernels were calculated by dividing the number of unpopped kernels by the total number of popped and unpopped kernels.

Compositional and Flavor Analysis of Popped Kernels

Popped kernels of each flake polymorphism were homogenized in a Blixer 3 blender for ≈20 sec and then analyzed for compositional attributes as for unpopped kernels. Additionally, amino acids were determined by acid hydrolysis in 6*N* HCl followed by derivatization using orthophthal-aldehyde-9-fluorenylmethyloroformate and then quantified using HPLC with fluorescence detection following the method described by Henderson et al (2000). Total dietary fiber was determined using the enzymatic-gravimetric method (Official Method 985.29; AOAC International 2010).

Volatile compounds for each popcorn flake polymorphism were characterized using solid-phase microextracton (SPME) coupled to gas chromatography-mass spectrometry (GC-MS). SPME is a semiquantitative technique widely applied for flavor analysis, as it simplifies extraction without using solvents by using an adsorbent silica fiber to partition analytes that can be desorbed using GC (Steffen and Pawliszyn 1996). A 0.5-g sample of homogenized popcorn was sealed in a 20-mL magnetic crimp top headspace vial with PTFE/silicone septa (Gerstel, Linthicum, MD). A 23-gauge, 85 μm carboxen/polydimethylsiloxane fiber was used for headspace sampling (Supelco, St. Louis, MO). The fiber was conditioned at 300°C for 1 hr before use according to manufacturers recommendations. The samples were analyzed with an Agilent 6890 GC coupled to an Agilent 5973 MSD, equipped with a Gerstel MPS2 autosampler, and a Phenomenex ZB-5 capillary column (60 m, 0.25 mm, i.d., 0.25 μm film thickness). The samples were equilibrated to 70°C for 10 min before exposing the fiber to the headspace for 25 min at 70°C. Equilibrium temperature of 70°C was used to increase partitioning of less volatile compounds into headspace while minimizing artifact formation. Then the fiber was immediately extracted in the GC injector in splitless mode at 280°C for 5 min, purge was switched on after 3 min to 30 mL/min. Helium was used as the carrier gas at constant flow (1 mL/min) with an average linear velocity of 26 cm/sec. The oven temperature was kept at 40°C for 3 min, then increased 4°C/min to 260°C, and held for 2 min (runtime 60 min). The mass selective detector (MSD) interface was held at 280°C. Using Chemstation MSD software (Agilent, Santa Clara, CA), electron ionization mass spectra were acquired at 70 eV in the m/z range 30–350 mass units. Flavor compounds were identified by comparing mass spectra to the NIST spectral library (Stein 2008).

Sensory Protocol and Evaluation

Using a central location test held over the course of a single day in Omaha, NE, 150 consumers evaluated three samples of the three popcorn flake shapes using a sequential monadic test design, in which samples were assigned random three-digit codes and evaluated blindly by panelists with serving order balanced and rotated to account for order and position effect (Peryam 1958). Consumers were asked to evaluate overall liking, appearance, shape, flavor, and texture liking for each of the three flake polymorphs using a 9-point hedonic scale, ranging from 1 (dislike extremely) to 9 (like extremely) with midpoint of 5 (neither like or nor dislike). In addition, intensity measures for overall flavor, butter flavor, saltiness, texture, crispness, crunchiness, and dissolvability were evaluated on a 10-point scale. Intensity measures degree of an attribute and not liking, so intensity ranges were described uniquely for each attribute tested. All panelists were recruited from the Automated Recruitment Calling System (ARCS) national database as head of household shoppers over age 18 that had purchased and eaten microwave popcorn at least three times in the past month and acceptors of butter-flavored popcorn. Consumers were given modest monetary compensation for their responses.

Immediately after popping in one of the seven aforementioned GE 1150W microwave ovens, popcorn was poured onto cooking trays that had been stored at 70°C in an industrial baking unit. Trained servers were assigned to sort for specific shapes to minimize sorting variability. Twelve pieces of each shape were sorted and served in 6-ounce polystyrene containers to consumers. Consumers were instructed to drink water and consume saltine crackers (unsalted tops) between each sample. Eight bags of fresh product were popped for every serving position, with additional bags popped on an as-needed basis. In this way, panelists received all samples at a similar temperature within 10 min of popping.

Data Analysis

All statistical analyses were performed using SAS software (v9.1, SAS Institute, Cary, NC). Pop performance and compositional data were analyzed using analysis of variance (ANOVA). Fisher's LSD test for mean separation was used to determine significance ($P \leq 0.05$) for all pop performance, compositional, and sensory evaluation data.

Volatile flavor data from SPME procedures were standardized to a baseline of 1.0 for each compound extracted from the bilaterally expanded flakes, which permitted relative comparisons to be made between peak areas for a given compound. In addition, volatile flavor analysis from GC-MS was imported and analyzed by principal component analysis (PCA), which simplified the measured flavor volatiles into a smaller number of principal components (PC) that account for most of the variance observed. PCA was performed in SAS using FACTOR procedures with a varimax rotation.

A mass balance was used to compare and identify any divergence between weighted average composition of popcorn flakes polymorphs to the expected composition from raw materials (unpopped kernels and slurry). Weighted average composition for popcorn flakes was calculated by multiplying measured analytical values for each flake polymorphism by percentage of the shape.

RESULTS AND DISCUSSION

Popping Performance by Flake Morphology

The total average expansion volume before sorting was 43.5 cm^3/g. Most kernels were bilaterally expanded (Table III). Unilaterally and multilaterally expanded kernels were significantly less

TABLE III
Distribution and Pop Performance Measures of Three Popcorn Flake Polymorphisms and Unpopped Kernels Produced After Microwave Popping

	Mean Values[a]			
	Unilaterally Expanded	Bilaterally Expanded	Multilaterally Expanded	Unpopped
Count	32.8b	263.2a	45.0b	27.8
Shape type or unpopped (%)	9.0b	71.2a	12.3b	7.6
Mass (g)	8.1b	54.9a	9.0b	4.0
Pop volume (mL)	232c	2360a	482b	–
Expansion volume (cm^3/g)	28.6c	43.0b	53.5a	–

[a] Values in same row followed by different letters indicate significant difference at $P \leq 0.05$ using Fisher's LSD; $n = 5$. (–) Means do not include unpopped data.

prevalent, while 7.6 ± 1.4% of kernels remained unpopped. The multilaterally expanded shape had the largest expansion volume, while the unilaterally expanded polymorphism had the smallest expansion volume.

During sorting, the unilaterally expanded shape appeared predominantly toward the bottom of the bag and was more yellow, shiny, and smooth in appearance than the other shapes, while the multilaterally expanded flakes were found more toward the top of the bag and had more pericarp visually exposed, giving a dry and rough appearance to the popcorn flakes. Granular mixes of different-sized objects separate by size in response to shaking or stirring with larger particles rising to the top (Rosato et al 1987; Jullien and Meakin 1990). One possible explanation for the distribution of flake shapes within the microwave popcorn bag is that the explosive force of kernels popping creates sufficient jostling within the bag to facilitate sedimentation, i.e., the larger multilateral expanded kernels rise toward the top surface, while smaller unilaterally expanded kernels shift into voids created underneath larger flakes and tend toward the bottom of the bag.

Another hypothesis for popcorn flake distribution is that kernels may pop differently depending on location within the bag. Those that expand unilaterally are those that are inhibited from full, multidirectional expansion because of the weight of the kernels above them. Bilaterally expanded kernels are in the middle of the bag, where there is some inhibition from the kernels on the top, but less than those on the bottom. Finally, multilaterally expanded kernels are those on the top of the bag and uninhibited from expansion.

Compositional and Flavor Analysis of Popped Kernels

The unilaterally expanded shape had significantly higher levels of total fat, saturated fat, total ash, potassium, and sodium than bilaterally and multilaterally expanded popcorn flakes (Table IV).

TABLE IV
Chemical Composition of Three Popcorn Flake Polymorphisms After Microwave Popping

	Mean Values[a]		
Analyte	Unilaterally Expanded	Bilaterally Expanded	Multilaterally Expanded
Total fat (%)	34.41a	30.24b	27.23c
Saturated fat (%)	16.81a	14.73b	13.05c
Trans fat (%)	0.09a	0.08ab	0.07b
Protein (%)	6.75c	7.31b	8.12a
Total ash (%)	2.76a	2.52b	2.54b
Sodium (mg/100 g)	767a	662b	621c
Potassium (mg/100 g)	216a	147b	202ab
Calcium (mg/100 g)	16.9a	17.2a	15.3a
Iron (mg/100 g)	2.1a	1.5a	2.0a
Phosphorus (mg/100 g)	260a	173a	263a
Total carbohydrates (%)	54.39c	57.71b	60.38a
Dietary fiber (%)	8.95a	8.94a	10.75a
Moisture (%)	1.69a	2.22a	1.73a

[a] Values in the same row followed by different letters indicate significant difference at $P \leq 0.05$ using Fisher's LSD; $n = 5$.

In contrast, the multilaterally expanded shape had the highest levels of protein and total carbohydrates and the lowest levels of fat, saturated fat, and sodium. While further investigation is required to determine the mechanisms and factors for forming various popcorn flake polymorphisms, it is noteworthy that unilaterally expanded flake shapes had the smallest expansion volume and highest levels of sodium and fat, while the multilaterally expanded polymorphism had the largest expansion volume and lowest level of sodium and fat. These results are consistent with the observations described above during sorting and suggest there may be an unbalanced distribution of oil slurry on kernels during the microwave popping. The unilaterally expanded kernels were located on the bottom of the bag where they were more exposed to the added fat and sodium, while the multilaterally expanded kernels tended predominantly to the top of the bag where there would be less exposure to added ingredients.

The weighted average composition of popcorn flakes using the composition for each polymorph was 30.93% fat, 7.53% protein, 59.05% carbohydrate, and 2.60% ash (Table V). Mass balance calculations using raw materials revealed that achieving equivalency to the weighted average flake composition necessitated ≈7.5% slurry not remaining with the popped kernels. While no published research has been found that quantifies the amount of slurry lost, observations in our laboratory suggest that 5–10% of slurry adheres to the inside walls of the packaging material during popping. Reducing this yield loss would seemingly offer a significant cost savings opportunity for the producer.

SPME-GC-MS procedures identified 48 volatile compounds in extracts of popped popcorn flakes, including several volatiles classified as aldehydes, pyrazines, and alcohols, and a singular lactone and glyceride compound. Multilaterally expanded popcorn flakes had significantly greater levels of 2,5-dimetyl-pyrazine, 2-ethyl-5-methl-pyrazine, 3-ethyl-2,5-dimethyl-pyrazine, and 2-methyl-pyrazine than the unilaterally and bilaterally expanded polymorphisms. On the other hand, multilateral flake shapes had significantly less of the lactone 2H-Pyran-2-one, tetrahydro-6-pentyl than did the other two shapes (Table VI).

PCA of these volatiles revealed grouping among similar popcorn flake shapes and differentiation between different flake polymorphs (Fig. 2). Principle component (PC) factors 1 and 2 accounted for a combined 73.9% of all variation in data. PC factors 3 and 4 accounted for an additional 9.9% and 5.0% of variation, respectively (not shown). While it is known that most foods are composed of many volatiles, only a limited number of particular volatile compounds are important to determine flavor (Grosch and Schieberle 1997). The main loadings for PC factor 1 included all pyrazine compounds, including 2,5-dimetyl-pyrazine, 2-ethyl-5-methl-pyrazine, 3-ethyl-2,5-dimethyl-pyrazine, and 2-methyl-pyrazine. Pyrazines have been associated with imparting characteristic popcorn-like aroma (Schieberle 1991; Buttery et al 1997). Loading for PC factor 3 included the lactone 2H-Pyran-2-one, tetrahydro-6-pentyl. Lactones have characterized sweet cream butter flavor (Mallia et al 2008).

TABLE V
Mass Balance Comparison of Raw Materials to Average Popcorn Flake Composition

	Weighted Average Composition Using Flake Polymorph Analyticals[a]	Theoretical Composition Using Raw Materials (no yield loss)[b]	Theoretical Composition with 7.5% Slurry Loss Applied
Total fat (g/100 g)	30.93	33.05	30.83
Protein (g/100 g)	7.53	7.04	7.30
Total ash (g/100 g)	2.60	2.94	2.80
Total carbohydrates (g/100 g)	59.05	56.97	59.07
Moisture (g/100 g)[c]	0.00	0.00	0.00
Total weight (g)	100.00	100.00	100.00

[a] Calculated by weighting actual analytical for each popcorn flake polymorphism with weighted 77.0% bilateral, 13.3% multilateral, and 9.7% unilateral.
[b] Calculated by weighting analytical values for raw materials.
[c] All mass balance calculations done on dry basis.

Sensory Evaluation

Overall consumer liking for the different popcorn flake shapes was 6.3–7.4 on a 9-point hedonic scale (Table VII). The unilaterally expanded polymorphism received significantly higher hedonic scores than the bilateral and multilateral shapes for overall liking and flavor liking. The unilateral and bilateral polymorphisms scored significantly higher than the multilateral shape for texture liking. Because test methodology presented samples to consumers without calling attention to shape, it is uncertain whether consumers detected flake shape differences. However, no statistical significance was observed for either appearance or shape liking. Significant differences were also observed between attribute intensities for the various popcorn flake polymorphisms (Table VIII).

The unilaterally expanded flake polymorph had the highest mean score intensities for overall flavor, butter flavor, saltiness, texture density, crispness, and crunchiness compared to the bilaterally expanded and multilaterally expanded flake shapes. In contrast, the multilaterally expanded flake polymorph had the lowest mean score intensities for overall flavor, butter flavor, saltiness, and crispness. Intensity scores for crunchiness and texture density for the bilaterally expanded and multilaterally expanded popcorn

TABLE VII
Consumer Sensory Mean Scores for Three Popcorn Flake Polymorphisms

	Mean Values[a]		
Measured Liking[b]	Unilateral	Bilateral	Multilateral
Overall product liking	7.4a	7.0b	6.3b
Appearance liking	7.6a	7.6a	7.4a
Shape liking	7.5a	7.5a	7.4a
Flavor liking	7.3a	6.8b	6.3b
Texture liking	7.3a	7.0a	6.5b

[a] Values in the same row followed by different letters indicate significant difference at $P \leq 0.05$ using Fisher's LSD.
[b] Liking scale of 1–9 for "dislike extremely" to "like extremely"; $n = 150$ total.

TABLE VI
Volatiles Obtained from Three Popcorn Flake Polymorphisms After Microwave Popping

	Mean Values[a]		
Analyte	Unilaterally Expanded	Bilaterally Expanded	Multilaterally Expanded
1-Decene	1.19b	1.00c	1.59a
1-Dodecene	0.98a	1.00a	0.75b
2,5-Cyclohexadiene-1,4dione,2-(1,1-dimethyetyl)	1.07a	1.00a	0.65b
2,6-Dimethyldecane	0.94ab	1.00a	0.91b
2-Dodecene, (Z)-	1.04a	1.00a	0.65a
2-Methoxy-4-vinylphenol	1.23b	1.00b	2.50a
2-Nonene, 3-methyl-, (E)-	0.69c	1.00b	1.50a
2-Trifluoromethylbenzone	0.68c	1.00b	1.21a
2H-Pyran-2-one, tetrahydro-6-pentyl	1.01a	1.00a	0.86b
3,5-Dimethyldodecane	1.07a	1.00ab	0.92b
3,5-Dimethyldodecane l	0.96a	1.00a	0.73b
Acetaldehyde	1.05ab	1.00b	1.09a
Acetonitrile	1.15b	1.00c	1.37a
Butane, 2,2,3,3-tetramethyl	1.23a	1.00a	1.19a
Butanoic acid, 2-butoxy-1-methyl-2-oxoethylester	1.10a	1.00a	1.10a
Cyclododecane	0.72c	1.00b	1.53a
Cyclopropane, nonyl-	1.08a	1.00a	0.54b
Cyclopropane, octyl-	0.71b	1.00b	1.66a
Cyclotetrasiloxane, octamethyl	1.02a	1.00a	0.45a
Decane	1.07a	1.00a	0.85b
Decane, 4-ethyl-	0.89b	1.00a	0.94ab
Dodecane	1.01a	1.00a	0.65b
Dodecane, 4-methyl-	0.88a	1.00a	0.97a
Dodecane l	0.85b	1.00a	0.85b
Ethanol	1.61b	1.00c	1.90a
Furan, tetrahydro-	0.98b	1.00b	1.37a
Furfural	0.75c	1.00b	1.53a
Hexadecane	1.26a	1.00b	0.48c
Hexanal	0.95b	1.00b	1.59a
Hexane	1.18a	1.00a	1.11a
Methyl Isobutyl Ketone	1.27a	1.00b	1.36a
Nonanal	1.05b	1.00b	1.60a
Nonane, 3-methyl-	0.92a	1.00a	0.93a
Nonane, 3-methyl-5-propyl-	0.88b	1.00a	0.98a
Oxirane, (ethoxymethyl)-	0.95a	1.00a	1.29a
Propanoic acid, 2-methyl-	0.87a	1.00a	0.90a
Pyrazine, 2,5-dimethyl-	1.03b	1.00b	1.86a
Pyrazine, 2-ethyl-5-methyl-	0.90b	1.00b	1.70a
Pyrazine, 3-ethyl-2,5-dimethyl	1.05b	1.00b	1.65a
Pyrazine, methyl-	0.76b	1.00b	1.38a
Tetradecane	1.11a	1.00a	0.49b
Toluene	1.32a	1.00a	1.45b
Triacetin	1.06a	1.00ab	0.96b
Tridecane, 3-methyl-	0.93a	1.00a	0.82b
Tridecane, 3-methyl-1	1.18a	1.00b	0.68c
Tridecane, 3-methylene-	0.86b	1.00a	0.87b
Undecane, 3-methyl-	0.89b	1.00a	0.87b
Undecane, 3-methylene-	0.79b	1.00a	1.10b

[a] Reported peak area standardized for each analyte relative to 1.00 for bilaterally expanded values. Values in the same row followed by different letters indicate significant difference at $P \leq 0.05$ using Fisher's LSD; $n = 4$.

TABLE VIII
Attribute Intensity Mean Scores for Three Popcorn Flake Polymorphisms

Intensity Measurement[b]	Mean Values[a]		
	Unilaterally Expanded	Bilaterally Expanded	Multilaterally Expanded
Overall flavor (1 = extremely weak to 10 = extremely strong)	7.1a	5.7b	4.9c
Butter flavor (1 = extremely weak to 10 = extremely strong)	7.0a	5.7b	4.8c
Saltiness (1 = not at all salty to 10 = extremely salty)	5.7a	4.8b	4.1c
Texture (1 = extremely light/fluffy to 10 = extremely dense/compact)	5.7a	4.7b	4.7b
Crispness (1 = not at all crisp to 10 = extremely crisp)	7.2a	6.3b	5.7c
Crunchiness (1 = not at all crunchy to 10 = extremely crunchy)	7.0a	6.0b	5.5b
Dissolvability (1 = extremely slow to 10 = extremely fast)	5.9b	6.3a	6.0ab

[a] Values in the same row followed by different letters indicate significant difference at $P \leq 0.05$ using Fisher's LSD.
[b] Intensity measured on a 10 point scale of 1–10. Intensity measures degree of an attribute (not liking); $n = 150$ total.

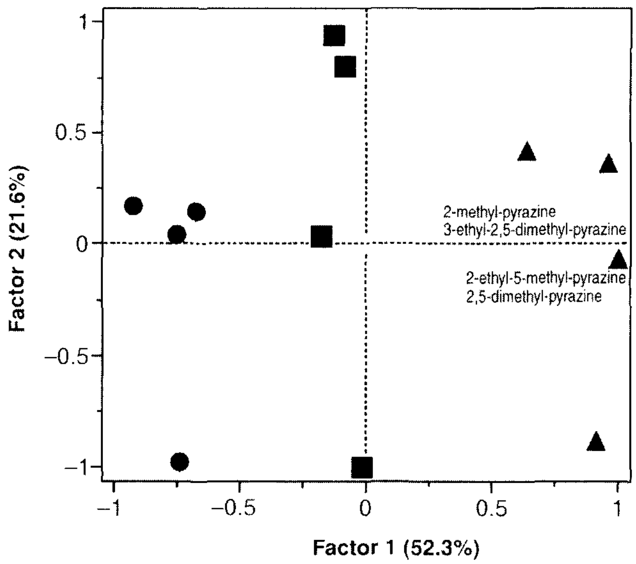

Fig. 2. PCA of volatiles grouped among similar popcorn flake shapes and differentiation between different flake polymorphs.

flakes were not significantly different from one another. Bilaterally expanded popcorn flakes had significantly faster dissolvability than unilaterally expanded flakes.

Relationship Between Composition and Sensory Measures

Unilaterally expanded popcorn flakes had the highest overall product liking in consumer testing despite having the smallest expansion volume, although the unilaterally expanded polymorph had the highest levels of total fat, saturated fat, and sodium, which correlates with the highest intensity mean scores for overall flavor, butter flavor, and saltiness. In contrast, multilaterally expanded flake polymorphs had the lowest overall product liking, highest expansion volume, lowest levels of total fat and saturated fat, and highest levels of protein, total carbohydrates, and popcorn-like aromatic pyrazines. Consumer panel mean score intensities for butter flavor correlate with volatile flavor results; multilaterally expanded flakes had the lowest levels of the lactone compound 2H-Pyran-2-one, tetrahydro-6-pentyl. Bilaterally expanded popcorn flakes showed overall product liking scores and fat and sodium levels between the unilateral and multilaterally expanded polymorphs.

The results from this study suggest that quality attributes beyond expansion volume and texture density of flakes are important considerations for consumer liking. Sensory evaluation showed that multilaterally expanded flakes had the least preferred texture despite having the highest expansion volume, although it may be that consumers simply prefer more oil and salt on popcorn because sensory attribute intensity results and compositional data showed that unilaterally expanded flake polymorphs had the highest levels of total fat and sodium.

CONCLUSIONS

Discernable popcorn flake polymorphisms can be identified and characterized even within a single hybrid of butterfly popcorn. Significant differences in expansion values, sensory hedonics, and compositional and flavor attributes exist between different popcorn flake shapes sorted after popping in a microwave oven. These results may assist commercial manufacturers in developing better methods for characterizing popcorn flake polymorphisms. Furthermore, given the potential impact to consumer acceptability, it may prove useful to research and gain a deeper understanding of factors that affect popcorn flake polymorphism.

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