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ORIGINAL ARTICLE

Sensory and Consumer Sciences

Relationship between sensory perceptions and volatile and phenolic compounds of fresh basil (*Ocimum basilicum* L.) evaluated by multivariate statistics

Lara J. Brindisi[1] | Regina O'Brien[2] | Bernadette K. Hayes[2] | Shashikant Kotwal[1] | Qingli Wu[1,2] | James E. Simon[1,2] | Beverly J. Tepper[2]

[1]New Use Agriculture and Natural Plant Products Program, Department of Plant Biology, Rutgers, The State University of New Jersey, New Brunswick, New Jersey, USA

[2]Center for Sensory Science & Innovation, Department of Food Science, Rutgers, The State University of New Jersey, New Brunswick, New Jersey, USA

Correspondence
James E. Simon, New Use Agriculture and Natural Plant Products Program, Department of Plant Biology, Rutgers, The State University of New Jersey, 59 Dudley Road, Foran Hall Room 396C, New Brunswick, NJ 08901, USA.
Email: jimsimon@sebs.rutgers.edu

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Abstract: Sensory and phytochemical analyses were conducted on sweet basil (*Ocimum basilicum* L.) to investigate the impact of volatile and phenolic compounds on aroma, taste, and flavor by mouth. A trained panel evaluated seven accessions, including 'Aroma 2', 'Nufar', 'CB19', and four breeding lines developed by Rutgers for downy mildew resistance (DMR). The basils selected for this study displayed unique sensory profiles that were chemically characterized with 21 volatile and 15 phenolic compounds using GC/MS and LC/MS, respectively. Principal component analysis revealed a two-factor model. Factor 1 described cinnamon, floral, ginger, lemon, and musty aromas, clustering with eucalyptol and many minor aromatic compounds. 'Rutgers Thunderstruck-DMR' closely aligned with these attributes. Factor 2 described an axis with clove aroma/flavor and bitter taste on one end and anise and sweet aroma/taste on the opposite end. Anise aroma/flavor was closely associated with methyl chavicol and sweet aroma/flavor. Eugenol and several phenolic acids clustered near bitter taste. However, not all phenolic acids contributed to bitterness or astringency, suggesting diverse roles in sensory perception. 'Aroma 2', 'Rutgers Passion DMR', and 'Rutgers Obsession DMR' were aligned with the clove/spicy/bitter pole of Factor 2, whereas 'CB19' was oppositely aligned with the anise/sweet pole. 'Nufar' and 'Rutgers Devotion DMR' occupied the center of the plot and were characterized as moderate in their sensory/phytochemical profiles. In conclusion, this study reveals that new varieties can be distinguished by their sensory/phytochemical profiles and compared to commercial cultivars. Further, the inclusion of phenolic compounds led to more precise sensory/phytochemical descriptions of these varieties.

KEYWORDS
aroma, flavor, herbs, phytochemistry, taste

Practical Application: This research provides valuable insights into the aroma, flavor, and underlying phytochemistry of fresh basil, which can help improve its taste and quality for culinary use. Sensory scientists and breeders can use the tools presented in this study as a means of selecting basil varieties to identify 'off types' and enhance aroma and flavor profiles.

1 | INTRODUCTION

Basil (*Ocimum* spp.) is a popular culinary herb in the United States and around the world (Simon et al, 1990). Basil belongs to the mint family (Lamiaceae), which is well known for its diversity of aromatic plants, including lavender (*Lavandula* spp.), mint (*Mentha* spp.), oregano (*Origanum* spp.), sage (*Salvia* spp.), and thyme (*Thymus vulgaris*). Basil is widely used in fragrance, culinary, and pharmaceutical applications due to its desirable aroma and high essential oil yield (Dhama et al., 2021; Simon et al., 1990).

Basil is classified by essential oil chemotypes, such as the traditional sweet basil or Thai basil (*Ocimum basilicum*), Holy basil (*Ocimum tenuiflorum*, formerly *Ocimum sanctum*), and lemon basil (*Ocimum × africanum*, formerly *Ocimum citriodorum*), which all express unique aromatic profiles (Grayer et al., 1996; Koroch et al., 2017). *Ocimum basilicum* boasts substantial chemical diversity within the species, resulting in the classification of seven *O. basilicum* subtypes. Each accession yields 10–31 significant volatile compounds (Liber et al., 2011), yet only a few "major" compounds define each of the subtypes, including combinations of linalool (described as sweet-smelling), eugenol (spicy), methyl chavicol (anise), methyl eugenol (clove), and methyl cinnamate (cinnamon-like) (Liber et al., 2011; Zheljazkov et al., 2008). For example, the characteristic 'Genovese' or Italian-style basil (*O. basilicum* var. *basilicum*) produces high levels of linalool and 1,8-cineole (monoterpenes), with lower levels of methyl chavicol and/or eugenol and methyl eugenol (phenylpropenes), resulting in sweet-smelling, fresh, slightly licorice-like, and spicy or clove aromas (Du et al., 2023; Liber et al., 2011; Vieira & Simon, 2006). The aromatic contributions of additional volatile compounds present in lower concentrations, or "minor" compounds, are less understood.

Studies investigating the human sensory experience of basil in any form, particularly fresh sweet basil, are rare (Bernhardt et al., 2015; da Costa et al., 2014; Du et al., 2023; Lee et al., 2017; Liang et al., 2022; Patel et al., 2021; Sheen et al., 1991). Sensory descriptors for fresh and dried sweet basil and basil essential oils have included attributes such as spicy (anise, clove, cinnamon or cinnamate), camphoraceous (piney, cooling, numbing, minty), citrus (lemon, orange), earthy (soil-like, hay-like, green, woody), and sweet/floral. Since several of the aforementioned studies (Bernhardt et al., 2015; da Costa et al., 2014; Lee et al., 2017; Sheen et al., 1991) were conducted before a standardized lexicon for basil aroma was available, the reliability of these descriptors for discriminating basil varieties within and across studies may be limited. To address this gap, we developed (Lee et al., 2017) and then validated (Patel et al., 2021) a lexicon specifically for fresh basil aroma using a highly trained descriptive analysis (DA) panel, which is considered the most accurate method for obtaining quantitative sensory profiles of a food or beverage product (Meilgaard et al., 2007).

Expert-trained panels are considered the gold standard for linking sensory attributes to chemical composition, because they provide consistent, quantitative assessments of aroma, flavor, and taste attributes using a standardized lexicon (Meilgaard et al., 2007; Patel et al., 2021). Unlike gas chromatography–olfactometry (GC–O), which is subjective and limited by individual variability in olfactory sensitivity (Delahunty et al., 2006), expert panels reduce bias through rigorous training and consensus-driven evaluations. Additionally, while consumer studies provide valuable insights into preference and acceptance, they lack the precision and repeatability required to identify specific chemical drivers of sensory characteristics (Lawless & Heymann, 2010).

Using the developed lexicon, Patel et al. (2021) characterized unique aroma profiles across seven fresh basil accessions, including commercial varieties of lemon, Thai, and cinnamon basils, as well as four experimental lines of Italian-style basils bred at Rutgers University. Results showed that the sensory attributes were strongly linked to the volatile composition of the leaves identified by headspace (HS) GC. Robust relationships were observed between volatile compounds and sensory attributes: methyl chavicol and perception of anise aroma; citral and lemon aroma; methyl cinnamate and cinnamon-like aroma; linalool and sweet/floral aroma; eugenol and clove aroma; and 1,8-cineole and eucalyptus-like fresh aroma (Patel et al., 2021). However, this lexicon was limited to aroma attributes as "sniffed" through the nose.

Negative attributes such as bitterness and astringency that are perceived by mouth could also make an important contribution to basil flavor and perceived quality.

Phenolic acids are abundant in basil (Jayasinghe et al., 2003; Kwee & Niemeyer, 2011; Mahmoud et al., 2022) and are linked to bitter taste and astringency in other plants and plant products, such as tea (Chen et al., 2022; Soares et al., 2013) and wine (Choi et al., 2020). Major phenolic acids in basil include rosmarinic acid, chicoric acid, caffeic acid, and caftaric acid, though the concentrations of each compound differ between varieties and vary under their growing environment. Thus, obtaining a more complete understanding of the flavor of basil, including in-mouth perception of taste and flavor, should include the contribution of nonvolatile phenolic compounds to the oral profile.

Two main objectives of this study were to (1) expand our existing fresh basil lexicon to include taste and flavor by mouth and (2) link the sensory profiles to phytochemical composition, including volatile compounds and nonvolatile phenolic compounds. To the best of our knowledge, no studies have specifically examined the role of phenolic compounds in the sensory perception of fresh basil.

2 | MATERIALS AND METHODS

2.1 | Plant varieties, growing conditions, and harvest procedures

All varieties were sweet *O. basilicum* Italian-style basils and selected for varying stress resistances and aroma or flavor characteristics. 'Nufar' was initially developed for resistance to *Fusarium* wilt, and it is known to be high in methyl chavicol with a sweet licorice aroma (Dudai et al., 2002; Reuveni et al., 1998; Walters & Lopez, 2022). 'Aroma 2' was then developed to have a stronger and more characteristic basil aroma (Ciriello et al., 2021). CB19 is an advanced Rutgers breeding line selected for its chilling tolerance and is also high in methyl chavicol and licorice aroma (Ribeiro & Simon, 2007). 'Rutgers Obsession DMR', 'Rutgers Devotion DMR', 'Rutgers Passion DMR', and 'Rutgers Thunderstruck DMR' are Rutgers-bred downy mildew resistant (DMR) sweet basil varieties that are commercially available as Italian-style basils (McGrath, 2024; Pyne et al., 2015) and will be hereafter referred to as 'Obsession', 'Devotion', 'Passion', and 'Thunderstruck', respectively.

Rutgers DMR basil seeds were purchased from VDF Specialty Seeds, and 'Aroma 2' and 'Nufar' seeds were obtained from Johnny's Selected Seeds. The CB19 seeds were derived from an advanced breeding line developed by the Rutgers University basil breeding program and are not commercially available. Seeds were sown into 128-cell plug trays with a 3:1 mix of potting soil and vermiculite, with plastic covers to maintain high humidity until germination. At least eight plantlets of each variety were individually transplanted into 6″ round pots at the six- to eight-leaf stage. Plants were grown in a growth chamber at the Rutgers New Jersey Agricultural Experiment Station (NJAES) with a 16-h photoperiod, 26/22°C day/night temperature, and 65% relative humidity. A combination of CW fluorescent bulbs (Philips F96T12/CW/HO-O ALTO 110W) and incandescent bulbs (Westinghouse A15) were used for an approximate intensity of 300 μmol/m^2/s. Plants were watered as needed and fertilized with NPK 20-20-20 (JR Peters, Inc.) every 2 weeks at a strength of ∼375 ppm nitrogen, starting at the true leaf stage. No pesticides or herbicides were applied.

Mature leaves were harvested from the top two nodes of the plants no longer than 1 h prior to panel evaluations. Leaves for phytochemical analysis were grouped by variety in perforated plastic bags with a moist paper towel and stored in a cooler. All leaves were free from damage and deterioration. Leaves for volatile compound analysis were dried at 40°C for 72 h and stored at room temperature until analysis. Leaves for phenolic compound determination were freeze-dried and stored at −20°C until analysis.

2.2 | Panel recruitment and screening

Panelists were recruited via email from Rutgers University and the surrounding area. Inclusion criteria were participants aged 18–65 years and in good health with no taste or smell disorders. Eligible participants completed additional in-lab screening, including taste and smell acuity tests and verbal questionnaires to screen for communication skills. Two novice panelists were selected to join an ongoing panel of six members with >50 hours of DA training in agricultural products. A total of eight panelists ($n = 6$ female) participated in the study. The study received approval from the Institutional Review Board (IRB) prior to the onset of the research (IRB number Pro2024001259).

2.3 | Panel training

Panelists were trained using generic DA methodology. The two novice panelists received four sessions of basic sensory training and then joined the remaining six panelists to begin fresh basil training. Training sessions were held in the Department of Food Science at Rutgers University. One-hour training sessions were held twice per week for 12 weeks.

The previously developed lexicon for basil aroma was used as the starting point for training (Lee et al., 2017; Patel et al., 2021). Initial sessions focused on familiarization with the aroma lexicon, followed by lexicon and reference development for in-mouth sensory attributes, including flavor, basic taste, and trigeminal characteristics. Panelists were introduced to basil obtained from local supermarkets and basil grown in the Department of Plant Biology at Rutgers University that exhibited a range of sensory characteristics. References included natural products such as baking spices, lemon peel, and mint leaves. All references were freshly harvested or prepared within 1 h of each training session. The lexicon terms and references were edited and refined through panel consensus. The additional aroma and in-mouth sensory terms were then combined with the aroma terms developed previously to create the final lexicon (Lee et al., 2017; Patel et al., 2021). The final lexicon included 24 terms listed in Table 1. The final training sessions included panelist calibration through discussions on evaluation procedures and practice evaluations.

During the in-booth practice, panelists rated attribute intensity on 15-cm end-anchored line scales (0 = *None* to 15 = *Very Strong*) and were given immediate feedback on scale usage. Panel metrics were checked in the RedJade platform for confirmation of panelist agreement and overall performance. Only panelists (n = 8) who met the performance criteria were included in the formal evaluations.

2.4 | Panel evaluation

For each sample, three whole leaves were presented in a 2-ounce soufflé cup labeled with a blinding code. Seven basil varieties were evaluated in duplicate over two sessions. Each sample was evaluated once per session. Samples were presented monadically in a balanced randomized order. Evaluations were completed in individual booths under white lighting. Attribute intensity was evaluated using 15-cm end-anchored line scales (0 = *None* to 15 = *Very Strong*). Participants were first asked to rip one leaf along the midline and evaluate the aroma attributes. The two additional leaves were used for the evaluation of in-mouth attributes. Unsalted crackers and filtered water were provided as a palate cleanser during mandatory 90 s breaks. Panelists wiped their hands with a wet napkin between samples to reduce the carryover of basil aroma on the fingertips.

2.5 | Solvents and reference solutions for chemical analyses

Solvents (HPLC Grade) including acetonitrile (ACN), formic acid (FA), and methanol were purchased from Fisher Scientific. Pierce LCMS water was procured from Thermo Fisher Scientific. Phenolic standards, including apigenin, caffeic acid, caftaric acid, chicoric acid, chlorogenic acid, cinnamic acid, coumaric acid, epicatechin, ellagic acid, ferulic acid, gallic acid, *p*-hydroxybenzoic acid, protocatechuic acid, rosmarinic acid, and rutin, and *n*-alkane standard C_8–C_{20} were purchased from Sigma–Aldrich and ChromaDex Inc.

2.6 | Analysis of volatile compounds using HS-SPME-GC/MS

Plant material was ground and ~100 mg per sample was sealed in a 20-mL screw-cap GC vial in triplicate. Basil varieties were analyzed with a Shimadzu GC 2010 Plus Series via HS solid-phase microextraction (SPME) with the Shimadzu TQ8040 triple-Q MS with an AOC 6000 autosampler. Injections were extracted for 5 min at 250°C and desorbed for 2 min with an analysis time of 19 min. Samples were subject to a five-way split with a sampling time of 1 min. Helium was used as the carrier gas at a pressure of 47.7 kPa with a total flow of 2 mL/min and a column flow of 1 mL/min. The column was an SH-Rxi-5Sil MS fused silica capillary column of 0.25 µm thickness, 30 m length, and 0.25 mm diameter. The column oven temperature was set to 35°C for 4 min and then to 250°C at a rate of 20°C/min and held for 2 min. The ion source temperature was 200°C, and the interface temperature was 250°C. Mass spectra were observed from 4 to 16.75 min in the Q1 scan acquisition mode. Scan speed was 10,000 from 45 to 500 m/z. Volatile compounds were identified by comparison with their retention indices relative to the multiple *n*-alkanes and by the mass spectra fragmentation pattern of each component compared to published mass spectra (Adams, 2017). The volatile compounds were classified as major if they comprised >2% of the total relative percent area of the chromatogram and as minor if they comprised ≤2%.

2.7 | Phenolic compound analysis using UHPLC-QqQ/MS

Phenolic extracts were prepared by grinding and extracting ~100 mg of plant material in 5 mL of 80% methanol solution (80:20 methanol:water). Extracts were vortexed for 10 s, sonicated for 10 min, and incubated at room temperature for 30 min. Samples were diluted by combining 100 µL of extract with 900 µL of 80% methanol solution. Samples were centrifugated at 12,000 rpm for 10 min. The supernatant was directly injected into the LC system.

The instrument used for phenolic compound analysis was an Agilent 1290 Infinity II ultrahigh-performance liquid chromatograph (UHPLC) system interfaced with

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TABLE 1 Lexicon for sweet basil, aroma, flavor, mouthfeel, and taste by mouth.

Attribute	Attribute definition	Reference	Intensity
Aroma			
Anise	Anise/licorice	5 g of dried anise seeds	9
Clove	Clove	5 g of whole, dried cloves	9
Cinnamon	Methyl cinnamate (cinnamon-like)	Methyl cinnamate 100 ppm	9
Black pepper	Black pepper	5 g of dried, black peppercorns	9
Spicy	Characteristics of spice mixture where no specific aroma predominates	Mixture of ground cinnamon (0.75 g), clove (0.25 g), anise seeds (1.5 g), and nutmeg (0.5 g)	9
Earthy	Soil	Potting soil	6
Musty	Associated with damp, stale items	30 mL of spring water infused with 25 g of diced white mushroom	8
Green	Green leaves/grass	30 mL of spring water infused with *Alstroemeria* leaf	5
Lemon	Associated with all components of fresh lemons (peel, juice, flesh, and rind)	Fresh lemon, cut into quarters	9
Ginger	Fresh ginger	10 g of fresh-cut ginger root	9
Mint	Mint and mint family herbs	0.32 g of fresh-cut spearmint in 25 mL of spring water	4
Floral	Floral	Fresh tulips	5
Sweet	Sweet aromatics	Marshmallows	7
Flavor			
Anise	Anise/licorice	500 mL of spring water infused with 2 g of freshly crushed anise	5
Clove	Clove	500 mL of spring water infused with 1.5 g of freshly crushed clove	7
Black pepper	Black Pepper	500 mL of spring water infused with 5 g of freshly crushed pepper	6
Spicy	Characteristics of spice mixture where no specific aroma predominates	500 mL of spring water infused with spice mixture	7
Green	Green leaves/grass	30 mL of spring water infused with red romaine lettuce leaf	5
Musty	Associated with damp, stale items	30 mL of spring water infused with 25 g of diced white mushroom	6
Lemon	Associated with all components of fresh lemons (peel, juice, flesh, & rind)	500 mL of spring water infused with 25 g of lemon rind	6
Ginger	Fresh ginger	500 mL of spring water infused with 10 g of fresh ginger root	3
Mint	Mint and mint family herbs	500 mL of spring water infused with 5 g of fresh-cut spearmint	5
Mouthfeel			
Astringent	Astringent, puckering effect	0.5 g alum/500 mL spring water	5
Basic taste			
Sweet	Basic sweet taste	10 g sugar/500 mL spring water	5
Bitter	Basic bitter taste	0.4 g caffeine/500 mL spring water	6

Note: Infusions were prepared no more than 3 h before use and were made by steeping the flavor material in room temperature spring water for 20 min, then removing the flavor material.

an Agilent 6470 Triple Quadrupole (QqQ) MS with an electrospray ionization (ESI) source. The UHPLC was composed of a binary pump with a built-in online degasser, a temperature-controlled autosampler, and a column thermostat. The drying gas, sheath gas, and nebulizing gas were supplied using a Parker Balston NitroFlow60NA nitrogen generator. UHPLC gradient and MS conditions followed similarly to Lyu et al. (2021). The instrumental software was Agilent MassHunter Workstation LC/MS Data Acquisition B.08.00, Optimizer B.08.00, Qualitative Analysis B.07.00, and Quantitative Analysis B.07.01. An Agilent SB-AQ RRHD UHPLC column was used for compound separation. The particle size was 1.8 µm, and the column size was 150 × 2.1 mm with an SB-AQ guard column (2.1 × 5 mm, 1.8 µm). The mobile phase A was 0.1% formic acid (FA) in water, and the mobile phase B was 0.1% FA in ACN. The flow rate was 0.2 mL/min. The gradient was 4% to 40% B in 6 min, which was raised to 60% B from 6 to 10 min, then held at 60% B for 0.5 min before dropping to 4% B in 0.5 min. The column was equilibrated with 4% B for 1 min between injections. The column was maintained at 30°C using a thermostat. The injection volume was 2.5 µL. The autosampler was set to 4°C. Nitrogen was used as the nebulizing and drying gas. The nebulizer was set to 30 psi, and the drying gas was set to 300°C with a flow rate of 13 L/min. The sheath gas was set to 250°C with a flow rate of 12 L/min. Analyses were conducted using the multiple reaction monitoring (MRM) mode and an external standard mix up to 15 calibration points (~10,000–0.61 ng/mL), including apigenin, caffeic acid, caftaric acid, chicoric acid, chlorogenic acid, cinnamic acid, coumaric acid, epicatechin, ellagic acid, ferulic acid, gallic acid, *p*-hydroxybenzoic acid, protocatechuic acid, rosmarinic acid, and rutin.

2.8 | Statistical analysis

Panel performance analysis and attribute intensity ratings were evaluated in XLSTAT-Sensory v2021.3 (Addinsoft) and RedJade Sensory Software (RedJade). The statistical cutoff criterion for all tests was *p*-value ≤0.05. Attribute differences were analyzed using analysis of variance (ANOVA), followed by Duncan's multiple range test. Panelist, replicate, sample, and interaction terms were included in the model. Panelist performance was assessed through the inspection of panelist effects, replicate effects, and panelist-by-replicate interactions.

Phytochemical and correlational analyses were conducted in R/RStudio v4.1.3. Quantitative data for each chemical compound identified were analyzed independently by one-way ANOVA. Significant differences between varieties were determined with Tukey's HSD test using R/*foreign* v0.8.84 and R/*agricolae* v1.3.5 (de Mendiburu & Yaseen, 2020).

Principal component analysis (PCA) was conducted in R/*FactoMineR* v1.34 (Lê et al., 2008) using the mean panel rating for each sensory attribute. Only dimensions with eigenvalues >1.0 were accepted into the model. The mean concentration for each chemical was used in the model as supplementary data. The Pearson correlation coefficient (*r*) was calculated in R/baseR v4.1.3 to measure the linear correlation between sensory and chemistry attributes. Heatmaps were developed using R/*heatmaply* v1.3.0 (Galili et al., 2018) with hierarchical clustering using the hclust function.

3 | RESULTS AND DISCUSSION

3.1 | Sensory profiles and attribute ratings

ANOVA revealed overall sensory differences among the samples for anise, clove, spicy, and green aromas and flavors; floral aroma; musty and ginger flavors; bitterness; sweetness; and astringency (Table S1). Panelist performance data are also shown in Table S1. Although panelist effects and replicate effects were present in the data, this is not unusual in evaluations of fresh plant materials, which can vary widely from plant to plant and across evaluation sessions (Bavay et al., 2013; O'Brien et al., 2022; Talavera-Bianchi et al., 2010). In the present study, there were relatively few panelist × sample and panelist × replication interactions, and they did not affect the data in a systematic way. There were numerous statistical differences in the attribute ratings across samples and post hoc comparisons (Table 2). The sensory profiles of each basil accession are depicted visually in Figure 1a–g.

'Nufar' is an example of an Italian-style sweet basil characterized by a high anise impact, clove-like notes, and a sweet aroma (Walters & Lopez, 2022). The panel's description of 'Nufar' included the aforementioned attributes, as well as spicy, ginger, lemon, floral, mint, and green notes (Figure 1). Astringency and bitterness by mouth were also perceived for this variety. Notably, anise aroma and flavor impact were substantially higher for CB19 compared to 'Nufar', while astringency and bitterness were mostly absent from CB19 as compared to 'Nufar' (Table 2). Although both varieties are considered high-anise sweet basils, CB19 imparted more anise aroma and flavor while being less bitter and astringent than the commercial variety, 'Nufar'. Since bitterness and astringency could be considered negative attributes for some consumers (Drewnowski & Gomez-Carneros, 2000), their impact on fresh basil could influence consumer acceptance of these varieties. Thus, our goal of incorporating taste and flavor

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TABLE 2 Mean (± SEM) intensity ratings for sweet basil varieties.

	Obsession	Thunderstruck	Devotion	Passion	CB19	Nufar	Aroma 2
Aroma							
Anise	3.9 ± 0.7^{bc}	2.8 ± 0.6^{c}	3.7 ± 0.5^{bc}	4.3 ± 0.8^{bc}	7.7 ± 0.4^{a}	5.3 ± 0.7^{b}	4.6 ± 0.7^{bc}
Clove	3.1 ± 0.6^{ab}	3.2 ± 0.6^{ab}	1.8 ± 0.5^{b}	3.2 ± 0.5^{ab}	2.0 ± 0.6^{b}	2.3 ± 0.6^{ab}	3.9 ± 0.6^{a}
Cinnamon	2.0 ± 0.4	2.9 ± 0.6	2.4 ± 0.5	2.0 ± 0.5	2.6 ± 0.4	2.2 ± 0.6	2.5 ± 0.6
Black pepper	1.3 ± 0.4	1.1 ± 0.3	1.2 ± 0.4	1.4 ± 0.4	1.1 ± 0.4	1.1 ± 0.3	1.9 ± 0.4
Spicy	4.3 ± 0.5^{a}	4.4 ± 0.6^{a}	3.0 ± 0.7^{b}	3.1 ± 0.5^{b}	3.4 ± 0.6^{b}	3.6 ± 0.7^{ab}	3.9 ± 0.7^{ab}
Earthy	1.0 ± 0.3	1.1 ± 0.3	0.9 ± 0.2	0.6 ± 0.1	0.8 ± 0.3	0.8 ± 0.3	1.1 ± 0.3
Musty	0.7 ± 0.2	1.2 ± 0.3	1.0 ± 0.3	0.6 ± 0.1	0.6 ± 0.2	1.0 ± 0.4	0.6 ± 0.2
Green	1.8 ± 0.3^{ab}	2.5 ± 0.4^{a}	2.4 ± 0.3^{ab}	1.9 ± 0.4^{ab}	1.6 ± 0.2^{b}	2.3 ± 0.4^{ab}	2.7 ± 0.3^{a}
Lemon	1.9 ± 0.6	3.6 ± 0.5	2.8 ± 0.6	2.8 ± 0.6	2.3 ± 0.3	2.4 ± 0.7	2.7 ± 0.6
Ginger	2.6 ± 0.6	3.2 ± 0.6	2.7 ± 0.6	2.5 ± 0.5	2.9 ± 0.6	3.2 ± 0.6	2.6 ± 0.4
Mint	1.9 ± 0.3	2.3 ± 0.3	1.8 ± 0.2	1.9 ± 0.4	2.5 ± 0.3	2.6 ± 0.3	2.1 ± 0.3
Floral	1.7 ± 0.3^{ab}	2.6 ± 0.5^{a}	2.6 ± 0.4^{a}	2.2 ± 0.4^{ab}	1.3 ± 0.3^{b}	2.6 ± 0.5^{a}	1.6 ± 0.4^{ab}
Sweet	2.9 ± 0.6	2.9 ± 0.4	3.1 ± 0.5	2.9 ± 0.6	3.0 ± 0.5	3.0 ± 0.6	3.1 ± 0.5
Flavor							
Anise	2.3 ± 0.4^{b}	1.8 ± 0.4^{b}	2.4 ± 0.4^{b}	2.8 ± 0.7^{ab}	3.9 ± 0.6^{a}	2.4 ± 0.4^{b}	2.8 ± 0.6^{ab}
Clove	2.3 ± 0.4^{b}	2.1 ± 0.5^{b}	2.7 ± 0.5^{ab}	2.4 ± 0.4^{b}	2.2 ± 0.3^{b}	2.0 ± 0.4^{b}	3.5 ± 0.4^{a}
Black pepper	1.2 ± 0.2	1.3 ± 0.2	1.2 ± 0.3	1.9 ± 0.3	1.2 ± 0.2	1.6 ± 0.3	1.3 ± 0.3
Spicy	3.0 ± 0.4^{b}	3.3 ± 0.5^{ab}	2.7 ± 0.5^{b}	3.8 ± 0.5^{ab}	3.8 ± 0.5^{ab}	3.4 ± 0.5^{ab}	4.4 ± 0.6^{a}
Green	2.0 ± 0.4^{ab}	2.7 ± 0.4^{a}	2.2 ± 0.3^{a}	1.2 ± 0.2^{b}	1.9 ± 0.4^{ab}	2.2 ± 0.4^{a}	2.2 ± 0.4^{a}
Musty	0.7 ± 0.1^{ab}	1.0 ± 0.2^{a}	0.7 ± 0.2^{ab}	0.8 ± 0.2^{a}	0.5 ± 0.1^{b}	0.7 ± 0.2^{ab}	0.5 ± 0.1^{b}
Lemon	1.5 ± 0.3	2.1 ± 0.4	1.8 ± 0.4	1.5 ± 0.4	1.7 ± 0.5	1.0 ± 0.2	1.0 ± 0.3
Ginger	0.9 ± 0.2^{b}	1.8 ± 0.2^{a}	1.0 ± 0.2^{ab}	1.5 ± 0.3^{a}	1.6 ± 0.4^{a}	0.9 ± 0.2^{b}	1.2 ± 0.2^{a}
Mint	2.2 ± 0.3	2.9 ± 0.4	2.5 ± 0.3	2.4 ± 0.4	2.9 ± 0.4	2.6 ± 0.4	2.6 ± 0.4
Mouthfeel							
Astringent	2.5 ± 0.4^{ab}	1.8 ± 0.4^{b}	2.2 ± 0.3^{ab}	2.9 ± 0.4^{a}	1.9 ± 0.5^{b}	2.4 ± 0.4^{ab}	2.6 ± 0.4^{ab}
Basic taste							
Sweet	1.3 ± 0.3^{b}	1.2 ± 0.4^{b}	1.2 ± 0.2^{b}	1.0 ± 0.3^{b}	2.3 ± 0.4^{a}	1.1 ± 0.3^{b}	0.9 ± 0.3^{b}
Bitter	2.7 ± 0.5^{b}	2.6 ± 0.4^{b}	3.4 ± 0.4^{ab}	3.7 ± 0.4^{a}	1.7 ± 0.4^{c}	3.1 ± 0.5^{ab}	3.6 ± 0.3^{a}

Note: Mean values in the same row with different superscript letters (a, b, c, etc.) differ at p-value <0.05.

by mouth into the basil lexicon provided more comprehensive insights into the eating quality of these varieties, which would have been missed without the in-mouth assessment.

'Aroma 2' is considered a classic sweet Italian style variety expressing a bouquet of anise, clove, and spicy notes (Ciriello et al., 2021). Consistent with this observation, we found that 'Aroma 2' was lower in anise aroma and higher in clove aroma than CB19. Notably, 'Aroma 2' was higher in bitterness and lower in sweetness than CB19 (Table 2). These descriptions support the characterization of 'Aroma 2' as having a complex, spicy profile that also imparts some bitterness by mouth. This profile is distinct from those of the high-anise varieties (Figure 1).

Since the Rutgers DMR basils share a common pedigree, they were expected to show similar sensory characteristics. Indeed, few robust differences were observed across these basils, and when differences were present, they were observed between 'Passion' and the other DMR varieties. Specifically, 'Passion' (and 'Thunderstruck') had more ginger flavor than 'Obsession' and less green flavor than both 'Thunderstruck' and 'Devotion' (Table 2). With respect to oral sensations, 'Passion' was more astringent than 'Thunderstruck' and more bitter than both 'Thunderstruck' and 'Obsession' (Table 2). Together, these data suggest that the DMR varieties exhibit similar overall sensory profiles with small, nuanced differences among them (Figure 1). The only exception to this pattern was that 'Obsession' and 'Thunderstruck' had a spicier aroma than 'Devotion' and 'Passion', but this difference was not observed for spicy flavor by mouth. Thus, the importance of this aroma difference is uncertain.

Although the Rutgers DMR basils are genetically unrelated to 'Aroma 2', their sensory phenotypes were similar;

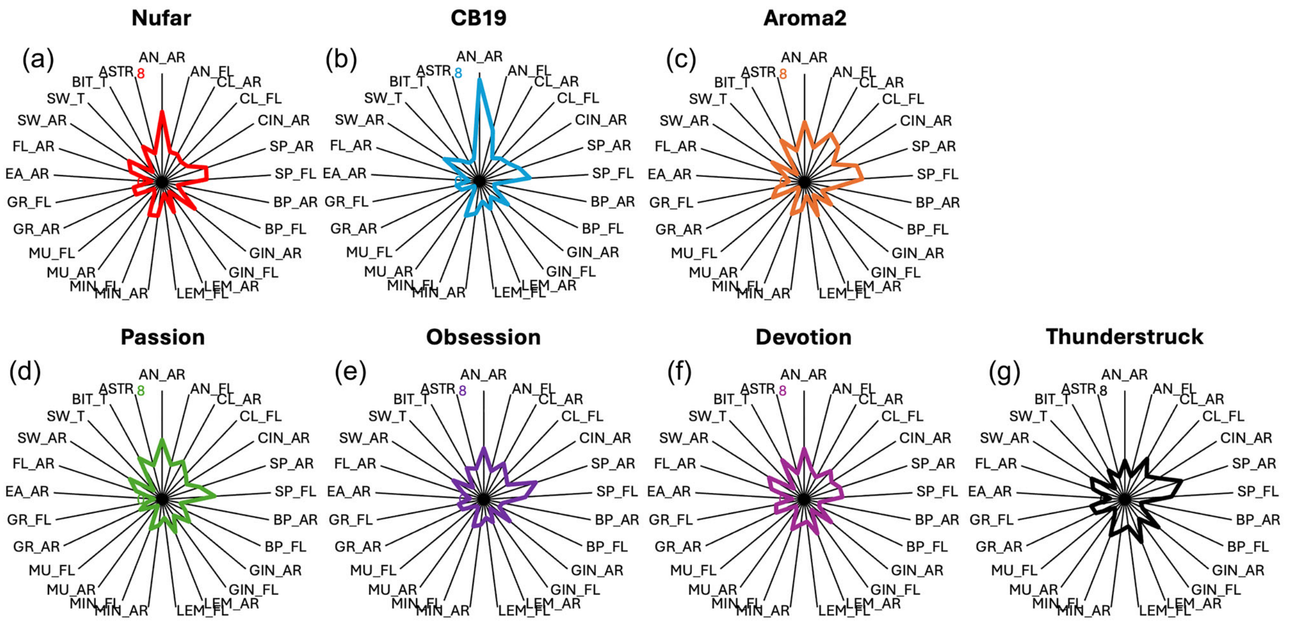

FIGURE 1 Radar plots of the descriptive profiles of seven varieties of sweet basil. Attribute names are listed around the perimeter of each plot and are defined in Table 2. Attribute abbreviations (first two letters) are as follows: AN, anise; CL, clove; CIN, cinnamon; SP, spicy; BP, black pepper; GIN, ginger; LEM, lemon; MIN, mint; MU, musty; GR, green; EA, earthy; FL, floral; SW, sweet; BIT, bitter; ASTR, astringent. Sensory abbreviations (second two letters) are as follows: AR, aroma; FL, flavor; T, taste.

all four basils exhibited different variations of complex spicy aromas and flavors (Figure 1). The aroma descriptions of the Rutgers DMR basils examined here agree with the aroma profile developed by Patel et al. (2021) for SB22, a Rutgers basil breeding line that was used as a parent in the development of the Rutgers DMR basils (Pyne et al., 2015). In this earlier study, SB22 was described as complex and spicy with some clove notes. The commonalities in the aroma descriptions of Rutgers basils across studies imply that the lexicon is reliable and capable of characterizing subtle sensory differences within related breeding lines.

Conducting consumer studies would be a necessary next step in assessing the market value of DMR varieties. In a preliminary consumer study (n = 188), we investigated the acceptability of fresh tomato–basil salads made with three of the DMR varieties described here ('Obsession', 'Devotion', and 'Thunderstruck'). Results showed that 'Obsession' was preferred over both 'Devotion' and 'Thunderstruck' (O'Brien et al., 2019). Vigorous breeding programs should evaluate not only agricultural parameters, such as disease resistance and other growing traits, but also their sensory impact and consumer acceptability to construct a holistic view of the potential for market success of new varieties. The present study provides valuable tools for accurately describing the sensory perceptions of fresh basil.

3.2 | Volatile composition

A total of 21 volatile compounds were detected via HS-SPME-GC/MS and expressed as peak area (A/mg) for each variety (Table 3). All aroma compounds were significantly different across accessions with the exception of camphene and myrcene.

Among the major compounds, methyl chavicol was significantly more abundant in 'Nufar' and CB19 than the other varieties and was the highest in CB19. This is consistent with the sensory profiles of these basils, which the panel described as strong in anise aroma and flavor. Linalool, thought to be associated with the sweet/floral aroma of sweet basil, was not statistically different between 'Nufar' and CB19, although its abundance was four times higher in 'Nufar' compared to CB19. Eucalyptol, responsible for fresh, camphoraceous, and minty aromas in sweet basil, was prevalent in both varieties, although eugenol, associated with a clove-like aroma, was low in 'Nufar' and not detectable in CB19. These findings contrast with 'Aroma 2', which was perceived as spicy and had the highest abundance of eugenol and eucalyptol among all the samples tested.

Many minor compounds (≤2% percent of total volatile composition) were present in the basils examined here in varying concentrations. The contributions of minor volatile compounds to the aroma, taste, and flavor pro-

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TABLE 3 Mean (± SEM) concentrations of sweet basil volatile compounds in different varieties represented as peak area (A/mg) using GC/MS.

Compound	Obsession	Thunderstruck	Devotion	Passion	CB19	Nufar	Aroma 2
Major volatiles							
Linalool	60,414.3 ± 34,880.2^{b}	118,761.0 ± 68,566.7^{b}	364,194.1 ± 210,267.6^{a}	149,332.6 ± 86,217.2^{b}	28,663.8 ± 16,549.1^{b}	116,439.6 ± 67,226.4^{b}	56,452.5 ± 32,592.9^{b}
Methyl chavicol	836.9 ± 483.2^{c}	2,356.2 ± 1,360.3^{c}	2,048.1 ± 1,182.5^{c}	1,678.4 ± 969.0^{c}	85,156.9 ± 49,165.4^{a}	56,039.3 ± 32,354.3^{b}	3,287.9 ± 1,898.3^{c}
Eucalyptol	11,209.9 ± 6,472.1^{b}	97,517.8 ± 56,301.9^{ab}	69,061.9 ± 39,872.9^{ab}	4,946.5 ± 2,855.9^{b}	66,819.8 ± 38,578.4^{ab}	74,218.1 ± 42,849.9^{ab}	133,593.2 ± 77,130.1^{a}
Eugenol	698.9 ± 403.5^{b}	377.2 ± 217.8^{cd}	0.0 ± 0.0^{d}	458.0 ± 264.5^{bc}	0.0 ± 0.0^{d}	231.8 ± 133.8^{cd}	2,325.8 ± 1,342.8^{a}
Minor volatiles							
(*E*)-*α*-Bergamotene	352.4 ± 203.4^{b}	246.5 ± 142.3^{b}	1,166.7 ± 673.6^{a}	176.7 ± 102.0^{b}	1,168.5 ± 674.6^{a}	425.3 ± 245.6^{b}	1,088.7 ± 628.6^{a}
α-Muurolene	117.0 ± 67.6^{bc}	353.1 ± 203.8^{abc}	438.8 ± 253.3^{abc}	208.7 ± 120.5^{bc}	141.5 ± 81.7^{c}	596.4 ± 344.3^{a}	464.4 ± 268.1^{ab}
α-Pinene	226.0 ± 130.5^{b}	1,665.3 ± 961.4^{ab}	1,137.6 ± 656.8^{ab}	0.0 ± 0.0^{b}	1,171.0 ± 676.1^{ab}	1,518.9 ± 876.9^{ab}	1,965.4 ± 1,134.7^{a}
β-Longipinene	102.1 ± 59.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	139.4 ± 80.5^{b}	263.5 ± 152.1^{a}	348.9 ± 201.4^{a}
β-Pinene	619.6 ± 357.7^{ab}	3,999.1 ± 2,308.9^{ab}	3,530.5 ± 2,038.4^{ab}	210.0 ± 121.2^{b}	2,813.7 ± 1,624.5^{ab}	3,188.6 ± 1,840.9^{ab}	4,556.1 ± 2,630.5^{a}
Borneol	0.0 ± 0.0^{b}	900.3 ± 519.8^{a}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	308.5 ± 178.1^{ab}
Bornyl acetate	0.0 ± 0.0^{c}	0.0 ± 0.0^{c}	0.0 ± 0.0^{c}	237.6 ± 137.2^{b}	0.0 ± 0.0^{c}	0.0 ± 0.0^{c}	338.5 ± 195.4^{a}
Camphene	0 ± 0.0	267 ± 154.2	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0	0 ± 0.0
Camphor	624.2 ± 360.4^{abc}	494.0 ± 285.2^{bcd}	1,095.5 ± 632.5^{a}	914.4 ± 527.9^{ab}	0.0 ± 0.0^{d}	183.8 ± 106.1^{cd}	0.0 ± 0.0^{d}
Limonene	189.4 ± 109.3^{a}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	191.1 ± 110.3^{ab}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}
Myrcene	1,568.1 ± 905.3	4,378.8 ± 2,528.1	2,272.9 ± 1,312.3	2,367.0 ± 1,366.6	2,544.3 ± 1,469.0	2,226.7 ± 1285.6	2,872.2 ± 1,658.3
Ocimene	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	906.8 ± 523.5^{a}	1,055.2 ± 609.2^{a}
Sabinene	235.7 ± 136.1^{bc}	1,767.7 ± 1,020.6^{ab}	1,385.8 ± 800.1^{abc}	0.0 ± 0.0^{c}	1,350.0 ± 779.5^{abc}	1,522.4 ± 879.0^{abc}	2,167.8 ± 1251.6^{a}
Terpinen-4-ol	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	141.8 ± 81.9^{a}	0.0 ± 0.0^{b}
Terpinolene	0.0 ± 0.0^{b}	473.8 ± 273.6^{ab}	530.2 ± 306.1^{a}	0.0 ± 0.0^{b}	0.0 ± 0.0^{b}	112.9 ± 65.2^{b}	0.0 ± 0.0^{b}
γ-Cadinene	108.8 ± 62.8^{bc}	344.1 ± 198.6^{b}	717.1 ± 414.0^{a}	356.0 ± 205.6^{b}	0.0 ± 0.0^{c}	348.9 ± 201.5^{b}	325.1 ± 187.7^{bc}
γ-Terpinene	0.0 ± 0.0^{b}	658.9 ± 380.4^{ab}	477.9 ± 275.9^{ab}	0.0 ± 0.0^{b}	181.0 ± 104.5^{ab}	530.1 ± 306.1^{a}	625.6 ± 361.2^{a}

Note: Mean values in the same row with different superscript letters (a, b, c, etc.) differ at *p*-value <0.05. Major volatiles (>2%) are ordered by abundance; minor volatiles (≤2%) are ordered alphabetically.

files of fresh or dry basil are not well understood. Nevertheless, minor volatile compounds can impart a variety of spicy/citrus/woody/and herbal aromas (Du et al., 2023; Patel et al., 2021) and should be examined given the nuances and different sensitivities across people (Delahunty et al., 2006; Meilgaard et al., 2007). Some of the more well-known compounds in basil include α-pinene, β-pinene, myrcene, and ocimene, among others (Liber et al., 2011; Vieira & Simon, 2006). How these compounds may be contributing to the sensory profiles of the basils tested here is described in more detail in the interpretation of the PCA biplots in Section 3.5.

3.3 | Phenolic composition

One objective of this study was to determine if phenolic compounds contribute to differences in the oral perception of sweetness, bitterness, and astringency of sweet basils. A total of 15 phenolic acids were surveyed against standard references in milligrams per 100 g via UHPLC–QqQ/MS (Table 4). Significant differences were detected for five phenolic compounds, including apigenin, caftaric acid, cinnamic acid, ellagic acid, and *p*-hydroxybenzoic acid. The observed varietal difference in caftaric acid stemmed from its absence in 'Nufar'. 'Nufar' also exhibited the highest abundance of apigenin and the lowest abundance of both *p*-hydroxybenzoic acid and ellagic acid relative to 'Devotion', which exhibited the highest abundance of these acids.

3.4 | Correlations and heatmaps

Pearson correlation coefficients were calculated to assess the relationships between the intensity of the sensory attributes and the phytochemical composition. As shown in Table S2, many of the correlations were statistically significant with high *r* coefficient values. Hierarchical clustering was used to construct heatmaps illustrating relationships between the varieties and the abundance of volatile compounds and phenolic acids (Figure 2).

3.5 | Principal component analysis

PCA was used to visualize the associations between the sensory and chemical profiles of basil accessions. A two-factor model was developed that explained 56.9% of the variance in the data. The biplot is shown in Figure 3. Factor loadings for the sensory and chemical attributes are shown in Tables S3 and S4.

Factor 1 (F1; 29.4%) included cinnamon and floral aroma, lemon aroma and flavor, ginger aroma and flavor, musty aroma and flavor, and green flavor. In addition to the major aromatic compound eucalyptol (fresh/camphoraceous) (Joint FAO/WHO Expert Committee on Food Additives, 2006; TGCS, 2021), many of the minor aromatic compounds clustered with these attributes on the right side of the plot, including α-pinene, (pine/earthy), β-pinene (woody/spicy), borneol (pine/woody/balsamic), camphene (fresh/camphoraceous) (Joint FAO/WHO Expert Committee on Food Additives, 2006; TGCS, 2021), myrcene (spicy/woody/herbaceous) (Rutnik et al., 2021; TGCS, 2021), sabinene (pine/woody/citrus), terpinolene (pine/citrus/herbal) (Liu et al., 2020; TGCS, 2021; Yu et al., 2004), and γ-terpinene (citrus/lemon/spicy) (Tamura et al., 2001; TGCS, 2021). While linalool is known to impart a sweet/citrus/floral aroma (Patel et al., 2021; TGCS, 2021), this compound was not a unique contributor to the factor analysis since it is ubiquitous across most varieties of sweet basils. Thus, linalool was not expected to distinguish the varietals examined here. Nevertheless, linalool was associated with lemon, floral, and ginger attributes on the right side of the plot. In contrast, limonene, often described as citrus peel-like, strongly loaded in the negative direction of the model and was situated on the far-left side of the plot. This dichotomy revealed a clear distinction between the "lemon" quality of these two compounds.

Factor 2 (F2; 27.5%) was characterized by clove aroma and flavor, black pepper aroma, bitterness, and astringency. The volatile compound eugenol and many of the phenolic acids previously described in the literature as bitter or astringent were strongly clustered together on this end of the axis (e.g., ellagic acid and caftaric acid) (Huang, 1991; Wu et al., 2024). Eugenol was expected to cluster with clove aroma and flavor, as it is the major component of clove oil (*Syzygium aromaticum*) (Cortes-Rojas et al., 2014). Anise aroma and flavor were closely associated with the compound methyl chavicol on this end of the axis, supporting previous basil sensory evaluations (Du et al., 2023; Lee et al., 2017; Patel et al., 2021), along with sweet aroma and flavor attributes. It is interesting to note that several phenolic compounds hypothesized to contribute to bitter taste in other plants or plant products, such as chlorogenic acid (Buffo & Cardelli-Freire, 2004; Heo et al., 2020), rosmarinic acid (an acid ester of caffeic acid) (Frank et al., 2007), and rutin (Li et al., 2019), did not associate with bitter taste and astringency in the basil varieties examined here. Historically, basil breeding programs have focused on traits related to field performance and aroma, and much still remains to be known about taste and flavor compounds. Future studies could examine in greater depth how specific

TABLE 4 Mean (± SEM) concentrations of sweet basil phenolic compounds in different varieties (mg/100g) using ultrahigh-performance liquid chromatography coupled with triple quadrupole mass spectrometry.

Compound	Obsession	Thunderstruck	Devotion	Passion	CB19	Nufar	Aroma 2
Phenols							
Apigenin	0.5 ± 0.3[b]	1.7 ± 1.2[b]	3.3 ± 2.3[ab]	3.3 ± 2.3[ab]	0.9 ± 0.6[b]	5.6 ± 4[a]	1.7 ± 1.2
Caffeic acid	23.1 ± 16.4	14.8 ± 10.5	34 ± 24	51.5 ± 36.4	7.7 ± 5.5	48.8 ± 34.5	13.3 ± 9.4
Caftaric acid	256.3 ± 181.2[a]	224.4 ± 158.7[a]	232.4 ± 164.3[a]	228 ± 161.2[a]	192 ± 135.8[ab]	0 ± NaN[b]	219 ± 154.9[a]
Chicoric acid	308 ± 217.8	214.6 ± 151.7	313.4 ± 221.6	314.7 ± 222.5	277.3 ± 196.1	524.5 ± 370.9	296.3 ± 209.5
Chlorogenic acid	1.6 ± 1.2	0.8 ± 0.6	1.3 ± 0.9	1.9 ± 1.3	5.3 ± 3.7	8.4 ± 5.9	0.9 ± 0.6
Cinnamic acid	67.9 ± 48[a]	12.6 ± 8.9[b]	10.2 ± 7.2[b]	9.6 ± 6.8[b]	32.5 ± 23[ab]	9 ± 6.3[b]	17.1 ± 12.1[b]
Coumaric acid	4.3 ± 3.1	6.5 ± 4.6	4.5 ± 3.2	3.4 ± 2.4	14.3 ± 10.1	11.3 ± 8	11.3 ± 8
Ellagic acid	115.2 ± 81.5[ab]	85.7 ± 60.6[ab]	164 ± 116[a]	141.2 ± 99.8[ab]	66 ± 46.7[ab]	59.2 ± 41.9[b]	106.4 ± 75.2[ab]
Epicatechin	177 ± 125.2	162.1 ± 114.6	162.3 ± 114.8	149.5 ± 105.7	157.3 ± 111.2	63.9 ± 45.2	148.9 ± 105.3
Ferulic acid	161 ± 113.9	24.4 ± 17.3	129.6 ± 91.7	126 ± 89.1	111.7 ± 79	174.7 ± 123.5	254.6 ± 180.1
Gallic acid	10.6 ± 7.5	51 ± 36.1	16.8 ± 11.9	18.6 ± 13.2	9.2 ± 6.5	4.8 ± 3.4	49.5 ± 35
p-Hydroxybenzoic acid	126.6 ± 89.5[ab]	97 ± 68.6[ab]	175.4 ± 124[a]	152.5 ± 107.9[ab]	77.4 ± 54.7[ab]	70.6 ± 49.9[b]	117.8 ± 83.3[ab]
Protocatechuic acid	1.5 ± 1.1	1.4 ± 1	1.7 ± 1.2	1.5 ± 1	2.3 ± 1.6	5.4 ± 3.8	1.6 ± 1.2
Rosmarinic acid	62.2 ± 44	45.4 ± 32.1	44.4 ± 31.4	41.5 ± 29.3	120.9 ± 85.5	94.4 ± 66.7	61.4 ± 43.4
Rutin	111.3 ± 78.7	88.5 ± 62.5	9 ± 6.4	30.7 ± 21.7	165.5 ± 117	169.3 ± 119.7	71 ± 50.2

Note: Mean values in the same row with different superscript letters (a, b, c, etc.) differ at p-value <0.05.

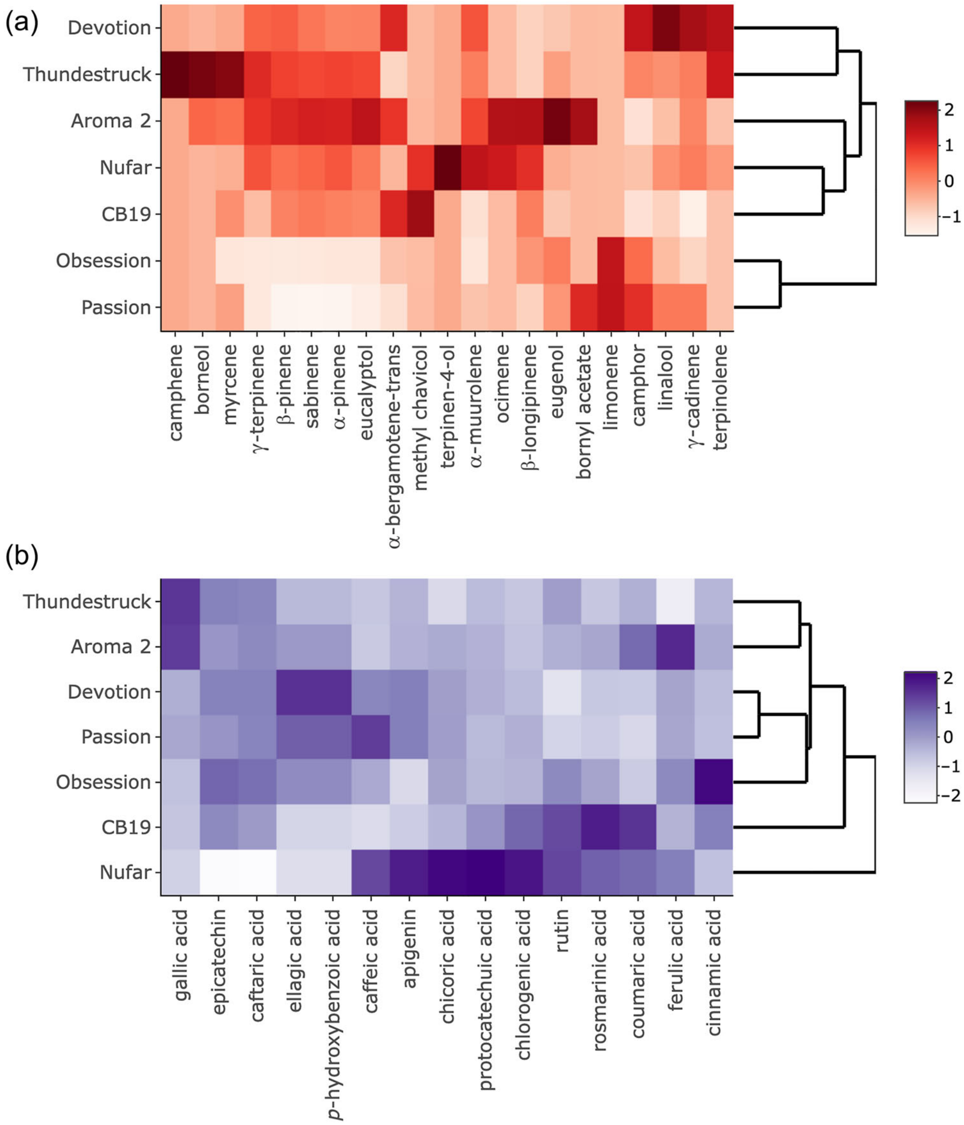

FIGURE 2 Heatmap of phytochemical concentrations determined in each variety. Dark red indicates high concentrations of a volatile compound (a), and dark purple indicates high concentrations of a phenolic compound (b). White indicates low concentrations of that chemical compound. Empirical normalization transformation was applied to each compound. Hierarchical clustering was used to create dendrograms for the accessions.

phenolic compounds influence bitterness or astringency in basil, particularly across different genetic backgrounds, life stages, and growth conditions.

Overlaying the basil varieties on the two-dimensional plot of the sensory and phytochemical attributes revealed important similarities and differences in the flavor profiles of these basils relative to their chemical compositions. Results showed that three of the basils occupied distinct positions in this space. Specifically, CB19 in the lower left quadrant was associated with anise aroma and sweetness and high methyl chavicol content. CB19 also exhibited the highest sweetness and lowest bitterness of the basils tested. Eugenol was not detected in this variety.

The upper left quadrant was occupied by 'Aroma 2', characterized by high eugenol content with clove, black pepper, and spicy notes. 'Aroma 2' was closely associated with bitterness and astringency and many of the phenolic acids that contribute to these oral sensations. 'Passion' and 'Obsession' were located in this quadrant in close proximity to each other, as well as to the compound limonene, which is associated with a bitter citrus peel aroma. Indeed, 'Passion' and 'Obsession' were the only two varieties that had measurable amounts of limonene in this study.

'Thunderstruck' could be considered an outlier, as this variety was located at the extreme right side of the plot and also midway along the anise/sweet to clove/bitter axis

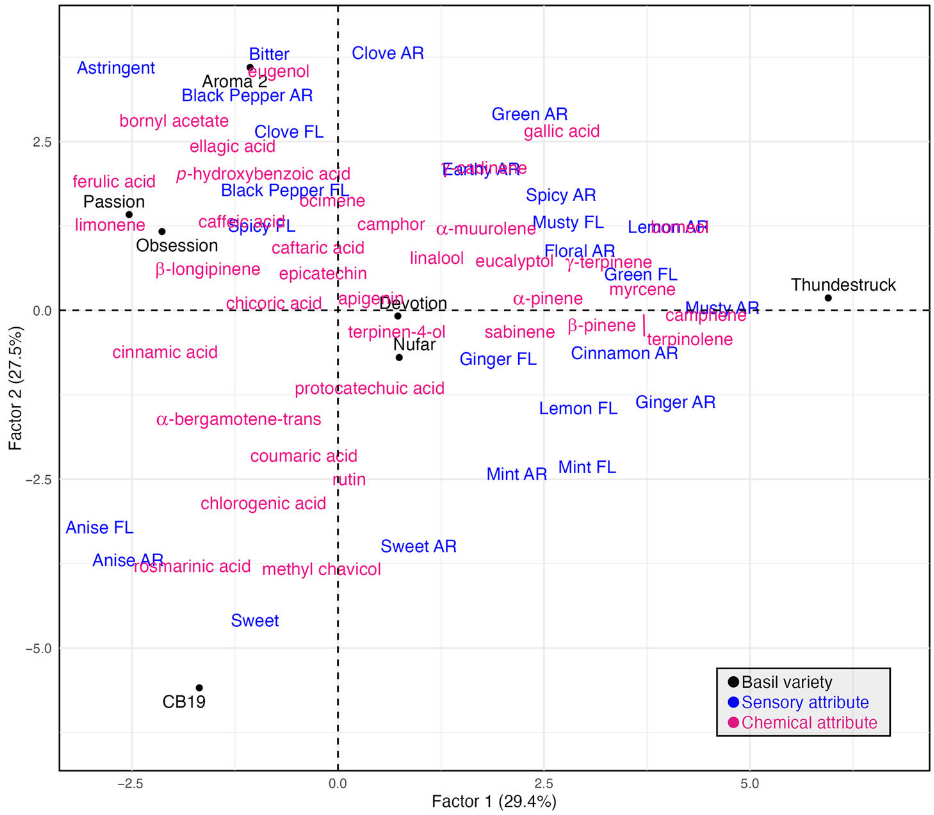

FIGURE 3 Principal component analysis (PCA) of basil varieties based on sensory attributes. Basil varieties are depicted in black, sensory attributes in blue, and chemical attributes in pink.

of this plot. The sensory profile of 'Thunderstruck' was associated with many of the secondary characteristics of a complex basil (e.g., spicy/woody, lemon, floral, ginger, minty) (TGCS, 2021) but was not distinctively anise-like or clove-like. 'Thunderstruck' was also closely associated with musty flavor and the compounds camphene and terpinolene on the PCA biplot. These compounds are described as having citrus/piney/minty/woody notes and noticeable medicinal qualities (TGCS, 2021). Although a musty flavor was noticed in all the samples at low intensities, 'Thunderstruck' was the only variety that contained camphene, while terpinolene was present in 'Thunderstruck', 'Devotion', and 'Nufar' at low concentrations. Mustiness is not a desirable sensory characteristic in foods (McGorrin, 2001), and the source of musty flavor in basil is not known. Nevertheless, we speculate that mustiness in 'Thunderstruck' might have been more noticeable in this variety due to the lack of characteristic spice notes and the presence of these medicinal compounds. These novel findings warrant further attention as we aim to understand the overall bouquet of basil aroma and the contributions of individual compounds to human sensory response.

Finally, 'Nufar' and 'Devotion' were located close together in the center of the plot. These two basils could be considered the least extreme of the varieties tested with modest sensory profiles characterized by spice, floral, ginger, and citrus notes and some bitterness.

4 | CONCLUSION

This study identified key candidate volatile and phenolic compounds underpinning the complex aromas and flavors of fresh sweet basil. As expected, the trained panel effectively discriminated basils exemplifying the main chemotypes of traditional basils (e.g., anise-like, clove-like), as well as cultivars from a common pedigree, which expressed distinctively different chemical compositions and sensory profiles. The ability to reliably distinguish the sensory–chemical profiles of related accessions, as demonstrated here, is critically important for establishing targeted breeding programs to enhance desirable traits in basil.

This study examined the role of phenolic compounds in the perception of bitterness and astringency in fresh sweet basil. Our findings suggest that some phenolic compounds are associated with bitterness and astringency in basil, while others are not associated with these attributes. These findings are preliminary and should be corroborated with additional studies that not only explore untargeted metabolites but also seek to better understand how many of the minor volatiles and nonvolatile phenolic compounds contribute to sensory perception. Nevertheless, the present data serve as a valuable starting point for further exploration of this topic.

AUTHOR CONTRIBUTIONS

Lara J. Brindisi: Data curation; formal analysis; visualization; writing—original draft; writing—review and editing; methodology. **Regina O'Brien**: Data curation; writing—review and editing; methodology. **Bernadette K. Hayes**: Data curation. **Shashikant Kotwal**: Data curation; formal analysis; validation; methodology. **Qingli Wu**: Methodology; writing—review and editing; validation. **James E. Simon**: Writing—review and editing; funding acquisition; validation; project administration; supervision; methodology; conceptualization; resources; investigation. **Beverly J. Tepper**: Writing—original draft; writing—review and editing; validation; conceptualization; supervision; project administration; methodology; resources; investigation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article and its Supporting Information.

ORCID

Lara J. Brindisi https://orcid.org/0000-0003-0325-5861
Beverly J. Tepper https://orcid.org/0000-0002-5033-6632

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SUPPORTING INFORMATION

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