Sensory Evaluation of Fruits and Selected Food Items by Descriptive Analysis, Electronic Nose, and Electronic Tongue

by

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Abstract

Sensory analysis has long depended on descriptive panels for systematic characterization and quality evaluation of food items. Currently, sensory instruments like e-nose (electronic nose) and e-tongue (electronic tongue) are also being implemented to aid in both descriptive and naïve panel evaluations. The present study employed all three techniques for evaluating the sensory attributes of selected food and fruit items. In the first part, the sensory profiles of different stevia blends with varying ratios of Reb A (Rebaudioside A), Reb D (Rebaudioside A), and Reb M (Rebaudioside A) were evaluated by a descriptive panel (*n* = 6) and e-tongue. The descriptive panel evaluation of bitter aftertaste ('bitter taste at 90 seconds') of stevia blends was well-correlated ($R^2 = 0.9116$) to the e-tongue analysis, suggesting its potential to discriminate and screen stevia blends. In addition, the consumer evaluation of stevia-sweetened ice cream (*n* = 41) was found to be acceptable although that of carbonated beverages (*n* = 39) was not satisfactory. PLSR (Partial Least Square Regression) revealed a significant correlation ($P < 0.05$) between stevia-blend descriptive analysis and consumer liking scores for ice cream and carbonated beverage. The second part explored the correlation between electronic senses (electronic nose and electronic tongue) and descriptive analysis of strawberries and blueberries. A significant correlation ($R^2 \geq 0.9095$) was observed between the descriptive panel ratings and e-nose and e-tongue analyses, demonstrating their high potential for the prediction of sensory qualities of these berries. The e-nose and e-tongue were found to be more sensitive than the human sensory panel because the discrimination indices of e-nose (DI ≥ 82) and e-tongue (DI ≥ 90) were very high even though the sensory panel did not find any significant differences in some sensory attributes of these berries. The major volatile compounds of both strawberries and blueberries consisted of esters, alcohols, aldehydes, furans, ketones, lactones, terpenes, and terpenoids with a total of 107 and 122

volatiles detected in strawberries and blueberries, respectively. The furaneol concentration (mg/mL) in strawberries had a significant positive correlation ($P < 0.05$) to overripe aroma (r = 0.806) and was negatively associated with green (r = -0.864), pungent (r = -0.704;), and floral (r = -0.651) aroma notes. The effect of elevated growth temperature appeared to affect the blueberry aroma resulting in the formation of more sulfurous volatile compounds with undesirable aroma notes as detected by the e-nose. However, e-nose headspace analysis could not identify any carboxylic acid or ester in blueberries grown at elevated temperature, which may be the reason of their significantly lower sourness scores as rated by the descriptive sensory panel than the ones grown at ambient temperature.

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List of Abbreviations

2-AFC	2-Alternative Forced Choice
Ace-K	Acesulfame Potassium
AHC	Agglomerative Hierarchical Clustering
ANOVA	Analysis of Variance
AT	Ambient Temperature
CAGR	Compound Annual Growth Rate
CDC	Centers for Disease Control and Prevention
DA	Descriptive Analysis
DI	Discrimination Index
E-nose	Electronic Nose
ET	Elevated Temperature
E-tongue	Electronic Tongue
FAO	Food and Agriculture Organization of the United Nations
FDA	Food and Drug Administration
FID	Flame Ionization Detector
GC	Gas Chromatography
GC-FID	Gas Chromatography - Flame Ionization Detector
GC-IMS	Gas Chromatography - Ion Mobility Spectrometry
GC-O	Gas Chromatography - Olfactometry
GC-MS	Gas Chromatography - Mass Spectrometry
GC-TOF-MS	Gas Chromatography - Time of Flight - Mass Spectrometry
GCMs	Global Climate Models
GMO	Genetically Modified Organisms

GRAS	Generally Recognized as Safe
HIS	High Intensity Sweeteners
HSD	Honestly Significant Difference
IRB	Institutional Review Board
LDA	Linear Discriminant Analysis
MACA	Multivariate Adaptive Constructed Analogs
NOAA-GML	National Oceanic and Atmospheric Administration - Global Monitoring Laboratory
NOAA-NCEI	National Oceanic and Atmospheric Administration - National Centers for Environmental Information
mg	Milligram
mL	Milliliter
OAV	Odor Active Value
PC1	First Principal Component
PC2	Second Principal Component
PCA	Principal Component Analysis
PLS	Partial Least Square
PLSR	Partial Least Square Regression
RCP	Representative Concentration Pathway
g-Reb A	Glycosyl Rebaudioside A
Reb A	Rebaudioside A
Reb B	Rebaudioside B
Reb D	Rebaudioside D
Reb M	Rebaudioside M
RS	Relative Sweetness
RSD	Relative Standard Deviation

STD	Standard Deviation
SE	Standard Error
SPME-GC-MS	Solid-Phase Microextraction Gas Chromatography - Mass Spectrometry
TI	Time Intensity
T_{max}	Daily Maximum Temperature
T_{min}	Daily Minimum Temperature
USD	United States Dollars
USDA	United States Department of Agriculture
USDA-NASS	United States Department of Agriculture - National Agricultural Statistics Service
USA	United States of America
VOC	Volatile Odor Compounds

CHAPTER 1. INTRODUCTION

As the world population is rapidly growing, the demand for better-tasting foods with acceptable quality is also on the rise. To ensure the quality acceptance of food items when they reach the fork from the farm, sensory analysis of these products is of utmost importance to retain their consumer appeal and satisfaction (Iannario et al., 2012). Sensory evaluation incorporates the application of smell, taste, sight, touch, and auditory sensations to determine food quality and acceptability by analyzing various food properties using standardized and reproducible scientific methods (Ruiz-Capillas & Herrero, 2021). Sensory analysis is particularly useful to food producers and processors for procuring meaningful insights in their products to simultaneously maintain consumer satisfaction along with much-desired commercial success (Endrizzi et al., 2013). Along with being a separate department on its own within the food and beverage industry, sensory evaluation is also essentially intertwined with new product development, marketing, quality control, and consumer research to comply with the verified set of standards put forth by regulatory agencies as well as for retaining brand value by satiating consumer needs and preferences (Muñoz, 2002; Murray et al., 2001). The realm of sensory science involves not only the food and beverage industry but also solid footprints in cosmetics, pharmaceuticals, personal care items, perfume and fragrance industry, to name a few (Kemp et al., 2018; Piggott et al., 1998).

Although various sensory evaluation techniques are currently being exercised in diverse food applications, DA (descriptive analysis) is regarded to be one of the fundamental bedrocks of sensory practices. The goal of DA is to attenuate human senses to derive reliable data that can be interpreted to obtain meaningful information about the sensory profile of a particular product (Meilgaard et al., 2016). There are several DA methods such as QDA® (Quantitative Descriptive

Analysis), QFP (Quantitative Flavor Profiling), RDA (Rank Descriptive Data), Spectrum™ method et cetera that requires training a group of assessors with adequate sensory capabilities using a set of protocol for a suitable period as detailed in their experimental procedures (Kemp et al., 2018). The DA has been utilized in a wide range of food products to profile their sensory characteristics. However, one of the most substantial uses of DA can be noted in optimizing the synergistic effect of blending various high-intensity sweeteners together to equate their sweetness intensity to that of sucrose which is known as iso-sweetness level with less pronounced bitterness. The effective implementation of DA has been carried out to characterize the sensory profiles and iso-sweetness levels of stevia, Reb A (Rebaudioside A), erythritol, tagatose (Gwak et al., 2012), luo han guo extract (monk fruit), xylooligosaccharides (Kim et al., 2015), and xylobiose (Park et al., 2017) equivalent to 5% sucrose. Besides, optimal flavor improvements could be achieved in sweeteners through DA by blending Reb A, Reb D (Rebaudioside D), and Rebaten G180 (glycosylated stevia) with sucrose, tagatose, allulose, and erythritol with minimal sensory off-notes (Jang et al., 2021).

The efficacy of DA is not only reinforced in the sensory optimization of sweeteners but also has provided critical sensory information in advanced breeding programs to propagate fruits with improved flavor profiles. A sensory lexicon for strawberries was developed using QDA by fourteen trained panelists for different aroma, flavor, appearance, and mouthfeel characteristics that could differentiate various strawberries based on cultivars, maturity, and flowering type with 86% variations explained by PCA (i.e., Principal Component Analysis) (Oliver et al., 2018). The QDA data of strawberries evaluated by 14 trained panelists were correlated to corresponding volatile analysis by HSPM-GC (i.e., Headspace Solid-Phase Microextraction–Gas Chromatography). An acceptable relationship was noticed between ‘floral’, ‘banana’, and ‘pineapple’ aroma notes and OAVs (i.e., Odor Active Values) of four esters (hexyl acetate, ethyl hexanoate, ethyl butanoate, ethyl 3-methylbutanoate) (Jetti et al., 2007). Strawberries were subjected to DA by an expert panel of fourteen assessors for various taste and flavor attributes to be associated with the volatiles identified by GC-MS (i.e., Gas Chromatography-Mass Spectrometry). Significantly higher correlation ($R^2 \geq 0.90$) was established between three esters’ concentrations (ethyl butanoate, methyl thioacetate, 3-methylbutanoate) and ‘strawberry flavor’ (Du et al., 2011). A multilingual lexicon was developed for blueberry sensory analysis to ensure consistent and robust evaluation procedure for a panel that may contain international judges with cross-cultural training and experience. The RATA (Rate-All-That-Apply) protocol validated by 16 trained judges demonstrated sophisticated competence of the lexicon for effective sensory evaluation of blueberries if conducted on a global scale with multinational panelists (Lippi et al., 2023). Eight blueberry cultivars were rated for different aroma attributes by a QDA panel of six expert judges on 10 line-scale. PLSR (i.e., Partial Least Square Regression) analysis suggested a positive relation ($r > 0.70$) between ‘grassy’ and hexanal and linalool, whereas eucalyptol was positively associated ($r = 0.665$) with ‘minty’ aroma (Cheng et al., 2020).

Along with human sensory evaluation, sensory instruments such as e-nose (electronic nose) and e-tongue (electronic tongue) are also gaining attention due to their application convenience. These electronic senses are the nondestructive, rapid, and cost-effective alternatives to regular analytical instruments with relative ease of operation (Tan & Xu, 2020). E-nose and e-tongue serve a wide variety of applications in food analysis to detect off-odors in foods, categorize food matrices based on their aroma and taste profiles, investigate contamination causes in foods (Cho & Moazzem, 2022). Prominent e-nose devices such as Heracles Neo e-nose (Alpha MOS, France) basically operates as a flash chromatography with a sensor array integrated for volatile detection

(Zhang et al., 2022). In comparison, commercial e-tongues like Astree e-tongue are liquid analyzers that use an array of sensors to translate the variations in electrochemical potentials sensed within the fluid matrix (Lvova, 2016). E-nose and e-tongue analyze the volatile and non-volatile flavor profiles of food matrices to generate odor maps and taste maps, respectively, using chemometric approaches such as PCA (Principal Component Analysis), LDA (Linear Discriminant Analysis) and so on (Han et al., 2014). These sensory instruments have been previously used to ensure food safety, quality control, regulatory compliance, and maturity stages in fruits (Bonah et al., 2020).

For example, the e-nose and e-tongue were combinedly employed in addition to a QDA panel of 10 expert judges for assessing orange and mandarin quality. The sensor responses of these instruments were significantly correlated to QDA sensory evaluation and GC-MS volatile analysis by PLSR to predict fruit quality in terms of sensory attributes and volatile profiles. It was suggested that e-nose and e-tongue were viable alternatives to costlier and more time-intensive options of GC-MS analysis and descriptive panel within citrus fruit industry (Qiu & Wang, 2015). Some pharmaceutical products are immensely bitter, and their descriptive analysis is very expensive and time-consuming since the panelists have to endure extreme bitterness throughout the training as well as taste evaluation. Berberine hydrochloride, a bitter drug utilized in traditional Chinese medicine, was analyzed by an e-tongue within 1.23–12.30 mg/mL concentration range. It was observed that the instrumental analysis was well-correlated to consumer sensory evaluation, which indicates the e-tongue’s high capability to predict sensory panel bitterness of berberine hydrochloride having unknown concentration. It was reported that human panelists could be substituted by the e-tongue as a safe, cost-effective tool to screen extremely bitter and yet-to-be-regulated medicinal products (Wang et al., 2013).

Adulteration is a dominant quality control issue in meat industry. Minced mutton adulterated with pork can be effectively identified using a fusion of e-nose e-tongue to safeguard meat quality control (Tian et al., 2019) Final product quality in dairy industry is ascertained by raw ingredients. An e-nose and e-tongue accompanied with a GC-IMS (i.e., gas chromatography-ion mobility spectrometry) were utilized to investigate how major additives impact infant formula flavor at processing stages. The volatile odor analysis by e-nose and GC-IMS and non-volatile profiling of milk matrix through e-tongue revealed demineralized whey powder to be potentially responsible for triggering off-odors in infant formula (Chi et al., 2022). Freshness is a prominent quality indicator in fish industry. The quality parameters in horse mackerel stored at −18°C for 3 months were assessed by combined application of e-nose, e-tongue, and colorimeter incorporated with chemometric analysis through data fusion. The superior prediction of fish freshness index by machine learning methods indicated superior efficacy of electronic sense fusion approach to evaluate frozen fish freshness (Li et al., 2023).

All these cited literatures indicate that descriptive panel or consumer evaluation can be complemented by sensory instruments such as e-nose and e-tongue to aid in informed decision-making in sensory analysis. Intrigued by similar research question about how well descriptive analysis of selected food and fruit items is complemented by their corresponding e-nose and e-tongue analyses, this current study was conducted keeping the following objectives in mind –

- Determining sensory profiles of different stevia blends mixed with various proportions of Reb A (Rebaudioside A), Reb D (Rebaudioside D), and Reb M (Rebaudiosode M) through descriptive analysis (Chapter 2).
- Investigating the potential of e-tongue to discriminate these stevia blends (Chapter 2).

- Assessing the consumer acceptance of ice cream and carbonated beverage sweetened with these stevia blends (Chapter 2).
- Evaluating changes in the sensory characteristics of strawberries and blueberries throughout 5 days of cold storage using a descriptive panel (Chapter 3).
- Understanding the potential of e-nose and e-tongue to detect the sensory changes in these berries (Chapter 3).
- Identifying the volatile aroma profiles of these berries through e-nose headspace analysis (Chapter 3).
- Establishing a relationship between furaneol (4-hydroxy-2,5-dimethyl-3(2H)-furanone) content in strawberry and descriptive aroma attributes (Chapter 3).

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CHAPTER 2. SENSORY PROFILES OF DIFFERENT STEVIA BLENDS AND THEIR APPLICATIONS IN SELECTED FOOD ITEMS

Abstract

The typical bitter aftertaste associated with popular steviol glycosides such as Reb (Rebaudioside) A, Reb D, and Reb M often affects the consumer acceptance of stevia-sweetened products. Hence, this present study was carried out to characterize the sensory profiles of seven stevia blends along with solo Reb A, D, and M solutions having iso-sweetness level of 9% sucrose with a descriptive panel (n = 6) and an e-tongue (electronic tongue). Furthermore, consumer acceptance testing (n = 82) was conducted to determine the acceptability of ice creams and carbonated beverages sweetened with the stevia blends. Significant differences ($P < 0.05$) were observed for "bitter taste" and "bitter taste at 90 seconds" among Ratio 3 (50% Reb A + 50 % Reb D), Ratio 6 (16.7% Reb A + 66.7% Reb D + 16.6% Reb M), and Ratio 7 (66.7% Reb A + 16.7% Reb D + 16.6% Reb M) through descriptive analysis. The e-tongue could discriminate stevia solutions based on their varying Reb percentages with a discrimination index of 89 to explain 85.04% total variability through principal component analysis. The PLSR (Partial Least Square Regression) analysis revealed that e-tongue data was highly correlated ($R^2 = 0.9116$) to the "bitter taste at 90 seconds" from the descriptive panel. Subsequently, consumer acceptance testing revealed that utilization of Reb M and Ratio 7 positively affected consumer liking of ice cream (6.10±0.29) and carbonated beverage (3.92±0.30), respectively. The PLSR correlation loading plots revealed that "anise/licorice" descriptive taste attribute of stevia blends was positively associated (r = 0.603) with the consumer liking of ice cream flavor but was negatively attributed (r = -0.846) to that of carbonated beverage flavor. To conclude, the blend ratios reported in this

study may help balance the bitter aftertaste of steviol glycosides with improved taste attributes in food applications which may prove to be potentially beneficial for the food and beverage industry.

1. Introduction

Steviol glycosides such as Reb (Rebaudioside) A, Reb D, and Reb M have been the focus point of recent sugar reduction strategies due to their non-caloric content with no adverse health effects (Heikel et al., 2012; Waldrop & Ross, 2014; Acevedo et al., 2018; Parker et al., 2018; Jung et al., 2021; Zhang et al., 2022). Extracted from *Stevia rebaudiana* (Bertoni) leaves, these major secondary metabolites of stevia are regarded as HISs (i.e., High-Intensity Sweeteners) because their sweetness intensity is 100–300 times higher than sucrose (Wang et al., 2023). Currently, stevia is only one of the two natural HISs that has FDA approval with GRAS (Generally Regarded as Safe) designation for human consumption and food applications (FDA, 2018). It is also permitted throughout Europe as an edible food additive with the E number "E-960" associated to it (EC, 2022). Further, every major regulatory agency throughout the world has mandated steviol glycosides as approved sweeteners with their use being noted in the food and beverage industries of more than 150 countries (Samuel et al., 2018). As compared to common artificial HISs such as sucralose, aspartame, Ace-K (i.e., acesulfame potassium) and so on, stevia neither disturbs the symbiotic microbiomes of human gastrointestinal tract nor does it cause metabolic problems (Srivastava & Chaturvedi, 2022). Being a natural zero-calorie sweetener, stevia is a healthy sugar substitute with no effect on blood sugar levels and insulin sensitivity (Ruiz-Ruiz et al., 2017). Consumption of stevia as a sweetener has been associated with reduced occurrence of obesity, diabetes mellitus, and hypertension. Besides, its beneficial effects have been documented for the prevention of dental plaque and caries among stevia consumers (Ahmad et al., 2020). For these reasons, stevia has become the sweetener of choice for people who want to cut off sugar from their diet (Rai & Han, 2022).

Obesity is a worrisome public health issue not only in the US (United States) but also from a worldwide standpoint as it is directly associated with higher risks of heart disease and early mortality (Alhasan et al., 2023). The alarming rise in obesity is the main reason for the untimely demise of over 4 million individuals all around the world (FAO, 2022). High intake of dietary sugar combined with low physical activity are the main contributors to obesity in young adults eventually leading to type-2 diabetes and cardiovascular problems in the U.S. (CDC, 2023). Additionally, excess sugar consumption has been linked with the occurrence of cardiovascular disease, hyperuricemia, fatty liver, and frequent prevalence of insulin sensitivity, dyslipidemia, and type-2 diabetes irrespective of weight gain via excessive calorie intake (Stanhope, 2016). As a result, sugar alternatives such as stevia have garnered so much consumer appeal in the U.S. that total stevia consumption in processed food and beverages skyrocketed from 14.5 tons in 2008 up to 597 tons in 2018 (Statista, 2023). In 2021, the value of the stevia market was reported to be worth 790.6 million USD (United States Dollars) globally with a growth forecast of 1642.8 million USD and 8.5% CAGR (i.e., Compound Annual Growth Rate) by 2030. This spectacular growth of the stevia market has been made possible thanks to the trending consumer willingness to replace sugar with healthier natural alternatives like stevia (Emergen, 2022).

As a result, the use of steviol glycosides such as Reb A, D, and M has gained immense popularity in food applications nowadays as non-caloric sweeteners. Compared to other artificial sweeteners and sugar substitutes, these natural sweeteners do not pose any adverse side effects on gut microbiota and human health in general (Schiatti-Sisó et al., 2023). However, Reb A is known to impart an undesirable lingering bitter aftertaste in the mouth that affects the sensory perception of consumers (Majchrzak et al., 2015). To avert this problem, it is either blended with minor steviol glycosides like Reb D and Reb M, or simply with sugar or other artificial sweeteners so that its bitter aftertaste can be masked (Jung et al., 2021; Zhang et al., 2022). In comparison, the aftertaste intensities of Reb D and M are less prominent than Reb A, but their extraction and processing costs are comparatively higher than those associated with Reb A because of very minuscule concentrations of Reb D and M in the stevia leaves as compared to abundant Reb A (Olsson et al., 2016). Due to this, Reb D and M may not be a cost-effective option for industrial-scale commercial use in the food industry, but it may be possible to mitigate the bitter aftertaste of steviol glycosides and lower their associated production cost simultaneously by blending these three steviol glycosides (Muenprasitivej, 2022). Blending of different sweeteners has proved to be an effective strategy to achieve a synergy of sensory acceptance with an improved balance of sweetness and bitterness typical of HISs (Waldrop and Ross, 2014). The binary mixture of 100 ppm Reb D + 300 ppm Reb M received higher liking scores for improved sweetness intensity, sweet aftertaste, and overall sweetness with reduced bitter aftertaste by sixty trained panelists (Prakash et al., 2014). The blend of glycosyl Reb A (0.0322%) with maltitol (7.6388%) in 1:1 ratio showed better sensory perception with less bitterness and astringency as compared to Reb A. (Jung et al., 2021). The blend of 50% Reb A + 50% erythritol scored significantly higher ($P < 0.05$) bitterness, whereas 45% sucralose + 55% erythritol exhibited sucrose-like flavor through Quantitative Descriptive Analysis conducted by twenty trained panelists which suggests that an optimal blend ratio of Reb A, D, and M will mask the bitter aftertaste typical of stevia while improving the sensory acceptance of stevia-sweetened products (Heikel et al., 2012). The sweetness intensity of different steviol glycosides was observed to be positively correlated with the number of glucosyl groups in their chemical structures which means that less glucosyl-containing stevioside along with rubusoside demonstrated faster sweetness perception and prolonged residual bitter aftertaste, whereas the temporal profiles of Reb D and M were characterized by later sweetness onset and quicker bitter aftertaste dissipation (Tian et al., 2022). In terms of bitterness, no significant difference ($P < 0.05$) was observed between the aqueous solutions of sucrose and Reb M whereas Reb A was significantly ($P < 0.05$) more bitter than sucrose, Reb D, or Reb M (Tao & Cho, 2020). Similarly, the use of steviol glycosides in ice cream production has revealed that the use of Reb D and M resulted in significantly better ($P < 0.05$) consumer preference ($n = 92$) than Reb A (Muenprasitivej et al., 2022).

The sensory profiles of sweetener blends can be effectively assessed when the data of trained human panel is complemented with that of an e-tongue for the purpose of discriminating and screening a vast number of mixtures (Waldrop and Ross, 2014). The e-tongue is an artificial gustatory device with a wide variety of applications in the food, beverage, and pharmaceuticals industry (Latha & Lakshmi, 2012). It mimics the human taste perception by analyzing the aqueous food matrix with a sensory array and then translating the electrochemical variations and potentiometric differences within the food solution in terms of basic tastes such as sweetness, bitterness, sourness, saltiness, and umami through various chemometric techniques such as PCA (Principal Component Analysis), DFA (Discriminant function analysis), LDA (Linear discriminant analysis) etc. (Tan & Xu, 2020). Due to its sensors' exclusive sensitivity towards fluid matrices, the e-tongue is limited to analyze only liquid samples since its sensor coatings cannot enact potential assessment in solid or gaseous specimen (Smyth & Cozzolino, 2013). The e-tongue has been productively implemented into diverse food and pharmaceutical applications. For example, it has been utilized for grading freshness of navel oranges and satsuma mandarins to screen fresh samples from stale ones (Li et al., 2023) and quantifying important wine quality parameters such as pH, tonality, total acidity, volumetric alcoholic degree (Gutiérrez et al., 2011). Moreover, the e-tongue can effectively predict the masking potency of HISs to envelop the extreme bitterness of medicines and pharmaceutical products (Zheng & Keeney, 2006; Rachid et al., 2010; Ito et al., 2013; Wang et al., 2013; Pein et al., 2015; Immohr et al., 2017; Guedes et al., 2021). Additionally, it has been widely used to evaluate oil quality (Buratti et al., 2018; Semenov et al., 2019; Blandon-Naranjo et al., 2023) and ascertain adulterants in wide variety of foods such as edible oils (Apetrei et al., 2014; Bougrini et al., 2014), water (Lvova et al., 2020), juices (Hong & Wang, 2014; Vitalis et al., 2021), honey (Bougrini et al., 2016; Oroian et al., 2018; Ciursa & Oroian, 2021; Wójcik et al., 2023), alcoholic beverages (Parra et al., 2006; Zaukuu et al., 2019), meat (Tian et al., 2019; Lu et al., 2021), and dairy products (Dias et al., 2009), to name a few. Recently, the effective applications of e-tongue to discriminate the standalone solutions of steviol glycosides such as Reb A, D, and M (Tao, 2020) as well as their binary mixtures (Muenprasitivej, 2022) have asserted the efficacy of this instrument to screen stevia blends with varying Reb ratios.

As it is evident from all the literature cited above, a significant amount of research focused on mixing different types of sweeteners to balance unpleasant flavor notes with optimized sweetness. However, very little data is available on the synergistic effect of blending Reb A, D, and M to achieve sucrose-like sensory attributes in food applications. Hence, the objective of this study was to find out an optimal stevia blend of Reb A, D, and M with better likability and lower bitter aftertaste through the descriptive analysis of an expert panel and subsequent application of the blends in ice cream and carbonated beverages. Another objective was to correlate the human descriptive analysis of these stevia blends with their corresponding e-tongue analysis to investigate the e-tongue's potential for discriminating different stevia blends.

2. Materials and Methods

2.1. Materials and Ingredients

Three different steviol glycosides namely Reb A, Reb D, and Reb M of 95% purity were purchased from Sweegen® (Santa Margarita, California, USA) and subsequently used in the descriptive analysis and electronic tongue analysis as well as in making ice creams and carbonated beverages. The water used throughout this study was 100% natural DeerPark® spring water (Chesapeake, Virginia, USA). The Great Value™ Unsalted Tops Saltine Crackers (Walmart Inc., Bentonville, Arkansas, USA) were used for cleansing palate between sample evaluations. All the materials and ingredients used in this study were labeled as non-GMO, food-grade ingredients and bought from local grocery stores (e.g., Publix, Kroger, Walmart, etc.) in Auburn, Alabama. The specific information on the materials and ingredients used in this study are listed in Table 2.1.

Table 2.1. Ingredients used for ice cream and carbonated beverage preparation with their specific brands.

Product	Ingredients	Brand and company information
Ice cream	Non-fat dry milk	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Heavy cream	Horizon Organic® (Ultra-pasteurized – Grade A, WhiteWave Services Inc., Broomfield, Colorado, USA)
	Polydextrose	Litesse® (DuPont Inc., Wilmington, Delaware, USA)
	Pure vanilla extract	Spice Islands® (Spice Islands Trading Co., Parsippany, New Jersey, USA)
Carbonated beverage	Pure anise extract	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Pure orange extract	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Pure vanilla extract	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Pure lemon extract	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Pure lime extract	McCormick® (McCormick & Co., Hunt Valley, Maryland, USA)
	Pure ginger extract	Home Choice (Home Choice Enterprise Ltd., St. Catherine, Jamaica, West Indies)
	Cinnamon ground	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Nutmeg ground	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Lavender flowers	Kroger® (The Kroger Co., Cincinnati, Ohio, USA)
	Caramel food color	Durkee® (ACH Food Companies Inc., Memphis, Tennessee, USA)
	Citric acid	Milliard™ (Milliard Brands, Lakewood, New Jersey, USA)

2.2 Iso-sweetness Determination of Different Steviol Glycosides

The 2-AFC (2-Alternative Force Choice) directional paired comparison test was conducted by Blue California Ingredients (Rancho Santa Mrgarita, CA) to confirm the theoretical iso-sweet values of Reb A, Reb M, and Reb D to a 9% sucrose solution. The sweetener solutions were presented in lidded 60-mL souffle cups with 3-digit codes, using a balanced presentation order. Figure 2.1 depicts a visual representation of 2-AFC Test.

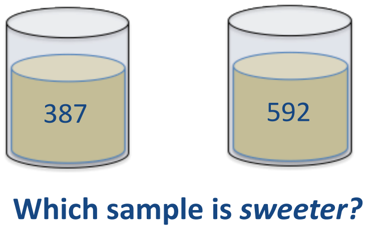

Figure 2.1. Visual representation of 2-Alternative Force Choice Test

Consumers for 2-AFC were employees of Blue California Ingredients (Rancho Santa Margarita, CA). Consumers ($n \geq 30$) were instructed to taste each Rebaudioside solution against the sucrose solution in the order presented. Panelists selected the sample they believed was sweeter. A 2-min rest period was enforced between each set of samples, during which panelists were instructed to rinse their mouths with filtered water and take a bite of an unsalted cracker. No more than two 2- AFC tests were conducted in one session. Data for 2-AFC testing were collected on iPads (Apple Inc., Cupertino, CA) using Compusense20 (Compusense, Guelph, Canada).

2.3. Descriptive Analysis of Stevia Blends

The descriptive analysis of stevia blends was carried out by Blue California Ingredients (Rancho Santa Margarita, CA) and the data was used for further analysis. Three different steviol glycosides namely Reb A, Reb D, and Reb M along with their different blend ratios as listed in

Table 2 were investigated for their sensory characteristics and subsequent food applications. The descriptive analysis of stevia blends was carried out by the employees of Blue California Ingredients (Rancho Santa Margarita, CA). A panel of 6 expert panelists highly experienced in sweetener evaluation judged a total of 10 samples as listed in Table 2.2 according to Spectrum™ Descriptive Analysis method by means of individual profiling.

Table 2.2. Sample description for different ratios of steviol glycosides.

Stevia blends	Reb A (0.060% concentration w/v)	Reb D (0.058% concentration w/v)	Reb M (0.043% concentration w/v)
Reb A	100.0%	0.0%	0.0%
Reb D	0.0%	100.0%	0.0%
Reb M	0.0%	0.0%	100.0%
Ratio 1	33.4%	33.3%	33.3%
Ratio 2	50.0%	0.0%	50.0%
Ratio 3	50.0%	50.0%	0.0%
Ratio 4	0.0%	50.0%	50.0%
Ratio 5	16.7%	16.7%	66.6%
Ratio 6	16.7%	66.7%	16.6%
Ratio 7	66.7%	16.7%	16.6%

Prior to the actual sample evaluation, the panelists received 3 weeks of sweetener-specific training and the attributes for the descriptive analysis were developed over the course of multiple training sessions. Each training session facilitated a warm-up calibration tray with standard basic taste water solutions. The samples were provided to the panelists with a balanced randomized presentation in 3-digit blinding codes following the Williams Latin Square design as modified by Compusense20 Cloud sensory analysis software (Compusense Inc., Guelph, Canada). All samples were served at room temperature (~23°C) with filtered water and unsalted crackers for palate cleansing purposes. Each sample was assessed in triplicates (*n* = 3) by the same judge for all descriptive taste attributes except "sweetness onset" according to a complete block design on a 15-

point intensity scale. A Spectrum-inspired 5-cm descriptive analysis scale was created to evaluate the “sweetness onset” of each stevia blends with 0 and 5 being the lowest and highest intensity, respectively. The trained panelists were asked to take ad libitum rest between the evaluation of each sample for minimizing carryover to the best of their abilities. The data of descriptive analysis were collected using Compusense20 Cloud sensory analysis software (Compusense Inc., Guelph, Canada). The consensus profiling for the descriptive analysis of each taste attribute was obtained through the exercise of rigorous individual observation as well as group discussion. The definitions of all 13 taste attributes around which the consensus was agreed upon are given in Table 2.3. The data of the descriptive analysis suggested that Ratio 3, Ratio 6, and Ratio 7 exhibited comparatively faster onset of sweetness and lower perception of bitter taste than the other ratios. Due to this, Ratio 3, Ratio 6, and Ratio 7 along with standalone treatments of Reb A, Reb D, and Reb M were used for the preparation and subsequent consumer evaluation of stevia-sweetened ice cream and carbonated beverages.

Table 2.3. All taste attributes and their definitions for the descriptive sensory analysis using a Spectrum-inspired descriptive analysis scale of different stevia blends.

Taste attributes	Definition	Reference	Scale type
Sweetness onset	Earliest perception of maximum sweetness sensation	Sucrose = 5 (very fast); Brazzein (Sweegen) = 1 (slow)	0-5 scale
Sweet taste	Basic taste elicited by sweeteners	Sucrose (5% in water = 5)	0-15 scale
Sweet Taste at 30 seconds	Sweetener-associated lingering sweetness sensation in the mouth for 30 seconds	Sucrose (5% in water = 5)	0-15 scale
Sweet Taste at 60 seconds	Sweetener-associated lingering sweetness sensation in the mouth for 60 seconds	Sucrose (5% in water = 5)	0-15 scale
Sweet Taste at 2 minutes	Sweetener-associated lingering sweetness sensation in the mouth for 2 minutes	Sucrose (5% in water = 5)	0-15 scale
Sweet Taste at 3 minutes	Sweetener-associated lingering sweetness sensation in the mouth for 3 minutes	Sucrose (5% in water = 5)	0-15 scale
Bitter taste	Basic taste elicited by various compounds including caffeine and quinine.	Caffeine (0.05% in water = 2)	0-15 scale
Bitter Taste at 90 seconds	Sweetener-associated lingering bitterness sensation in the mouth for 90 seconds	Caffeine (0.05% in water = 2)	0-15 scale
Sour taste	Basic taste elicited by organic acid (e.g., citric acid)	Citric acid (0.05% in water = 2)	0-15 scale
Metallic	The typical taste of metal spoon, coins, and/or blood	Ferrous Sulfate (0.005% in water)	0-15 scale
Anise/ licorice	The typical taste of anise and/or licorice	Anisic Aldehyde dissolved in water	0-15 scale
Astringency	Chemical feeling factor on the tongue or oral cavity described as puckering or dry	Alum (0.125% in water = 7)	0-15 scale
Thickness	The perception of how freely the liquid flows in the mouth (viscosity) rather than deforming due to applied force	Filtered water = 0.5; skim milk and water mixed at 1:1 ratio = 1, Skim milk = 3	0-15 scale

2.4. Electronic Tongue (E-tongue) Analysis of Stevia Blends

The a-Astree e-tongue (Alpha MOS, Toulouse, France) was used to generate the taste maps of all stevia blends in terms of PCA plots using the protocol previously validated by Tao & Cho (2020) and Muenprasitivej (2022). Before running the analysis sequence, seven potentiometric sensors namely AHS, CTS, NMS, PKS, CPS, ANS, and SCS incorporated in the #6 sensor array of the e-tongue were submerged into deionized water for 30 minutes to hydrate the sensors' coated membrane so that proper conditioning could facilitate accurate measurement of voltage difference in the sample being analyzed. At first, standard solutions of HCl, NaCl, and MSG (monosodium glutamate) having 0.01 M concentration were used to carry out the conditioning and calibration of the e-tongue followed by diagnostic cycles before any type of analysis could be performed. Afterwards, around 20 mL of all samples as given in Table 2.2 namely Reb A, Reb D, Reb M, Ratio 1, Ratio 2, Ratio 3, Ratio 4, Ratio 5, Ratio 6, and Ratio 7 were transferred into e-tongue beakers and placed in the autosampler for analysis.

2.5. Stevia-sweetened Ice Cream Preparation

The ice cream was prepared following the slightly modified method of Muenprasitivej et al. (2022). Muenprasitivej et al. (2022) prepared the ice cream at the same concentrations of Reb A, D, and M (9%), but in this present study, we used the iso-sweet concentrations of Reb A, D, and M equivalent to 9% sucrose concentration, which were determined to be 0.060% Reb A (w/v), 0.058% Reb D (w/v), and 0.043% Reb M (w/v), respectively. These iso-sweetness levels of Reb A, D, and M were used to calculate their corresponding percentages in Ratio 4 (50% Reb A + 50% Reb D), Ratio 5 (16.7% Reb A+66.7% Reb D+16.6% Reb M), and Ratio 6 (66.7% Reb A+16.7% Reb D+16.6% Reb M) pertaining the same sweetness perception of 9% sucrose concentration. The amount of each ingredient used for ice cream preparation along with their functionalities and caloric content is listed in Table 2.4. The column "Ice cream samples" in Table 2.4 denotes each specific treatment that varies according to their ratios of Reb A, D, and M as specified in Table 2 used in their formulations. At first, a KitchenAid® mixer (St. Joseph, MI, USA) was used to stir polydextrose, dry milk, and sweetener (e.g., Reb A, D, M) until they were mixed well with subsequent addition of warm water having around 43°C of temperature. When the mixture was properly homogenized and all lumps were entirely homogenized in the resultant solution, vanilla extract was introduced in the solution along with heavy cream while the mixture was being continuously stirred by the mixer. Afterwards, aging of the ice cream treatments was carried out at in a refrigerator at ~ 4°C temperature. After a 1-hour aging period, the aged ice cream mixer was run into Cuisinart® ice cream maker (Stamford, CT, USA) for another 1 hour to prepare ice cream. All treatments of the ice cream were prepared at least 48 hours prior to the consumer test and preserved at -20°C freezer using 1.8 L (64 oz) Rubbermaid® plastic containers (Atlanta, GA, USA) until sample evaluation for consumer test.

2.6. Stevia-sweetened Carbonated Beverage Preparation

The preparation of carbonated beverage using different stevia blends as listed in Table 2.5 was prepared in two steps. At first, syrups of each carbonated beverage treatments were formulated in the form of concentrated solutions. Then, these syrups were diluted with appropriate ratios of carbonated water to prepare carbonated beverage samples. First of all, all the ingredients except liquid caramel color and Rebaudiosides (i.e., Reb A, D, M) were placed into a saucepan of medium size and thoroughly mixed by hand with a spoon. Secondly, 6 pyrex mixing bowls were used to measure out the caramel color along with respective Rebaudioside treatments separately (see Table 2.5). Then, the saucepan containing liquid mixture was heated up to 100°C with lid uncovered over an electric stove (Viking® VER530, Greenwood, Mississippi). Afterwards, the saucepan was allowed to simmer at ~85°C over low heat of the stove for 20 minutes. A coffee filter was placed in between two fine-mesh metal sieves and the mixture in the saucepan was strained through the sieves directly into the mixing bowl containing caramel color and different stevia blends. To ensure proper homogenization, this new mixture containing all ingredients was blended well for 2 minutes using a hand-held immersion blender (Bella® Immersion Blender, New York City, NY). Then the resultant syrups of each specific treatment were transferred into airtight containers and kept in a refrigerator at ~4°C overnight. Plastic bottles of 1 L capacity (SodaStream®, Kefar Sava, Israel) were used to store 890 mL volume of cold water having ~4°C temperature and then subsequently carbonate the water for 10 seconds with a carbonator machine (SodaStream® E-Terra, Kefar Sava, Israel). Immediately after carbonation, the bottles were capped and then kept into the refrigerator (~4°C) for 30 minutes. Afterwards, 110 mL syrup of each stevia treatment were mixed with 890 mL of carbonated water to prepare carbonated beverages. Then the beverage bottles were sealed immediately with caps and kept inside the refrigerator (~4°C) until they were used for consumer testing of naïve panelists.

2.7. Calorie Content Estimation

Genesis R&D Software (ESHA Research, Oak Brook, IL, USA) for labeling and supplement formulation was used to estimate the caloric value of ice cream and carbonated beverages as mentioned in Table 2.4 and 5, respectively, prepared with different Rebaudioside treatments.

Table 2.4. Ingredients used for the preparation of different ice cream treatments along with their calories.

Ice cream samples	Ingredients used for ice cream preparation								
	Non-fat dry milk[1] (g)	Polydextrose[2] (g)	Heavy cream[3] (g)	Pure vanilla extract[4] (g)	Rebaudioside A[5] (g)	Rebaudioside D[5] (g)	Rebaudioside M[5] (g)	Water[6] (g)	Calories per 80.0 g serving size*
Reb A	97.14	169.99	277.53	3.47	0.60	–	–	450.98	120
Reb D					–	0.58	–		
Reb M					–	–	0.43		
Ratio 3					0.30	0.29	–		
Ratio 6					0.10	0.39	0.07		
Ratio 7					0.40	0.10	0.07		

[1] Flavor and texture enhancer; [2] Bulking agent; [3] Mouthfeel and texture enhancer; [4] Flavoring agent; [5] Sweetener; [6] Solvent (Muenprasitivej et al., 2022);
* Caloric content calculated by Genesis R&D Software;
Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively).
Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

Table 2.5. Ingredients used to prepare syrup of carbonated beverage and its calorie contents.

Ingredients	Carbonated beverage samples					
	Reb A	Reb D	Reb M	Ratio 3	Ratio 6	Ratio 7
Rebaudioside A (g)	0.50	–	–	0.25	0.08	0.33
Rebaudioside D (g)	–	0.50	–	0.25	0.33	0.08
Rebaudioside M (g)	–	–	0.50	–	0.08	0.08
Star anise extract (g)	0.05					
Orange extract (g)	0.83					
Vanilla extract (g)	0.30					
Lemon extract (g)	0.30					
Lime extract (g)	0.30					
Ginger extract (g)	0.74					
Cinnamon ground (g)	0.39					
Nutmeg ground (g)	0.27					
Lavender flowers (g)	0.46					
Caramel color (g)	4.75					
Citric acid (g)	2.83					
Water (g)	473					
Calories per 130 mL serving size*	0.00					

*Caloric content calculated by Genesis R&D Software

Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively).

Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

2.8. Consumer Testing for Ice Cream and Carbonated Beverages

Naïve consumers who were 18–65 years old and had a general liking for ice cream with at least 2-3 consumption frequency per month and drank carbonated beverages 2-3 times per week were selected from the faculty, staff, and students of Auburn University. Prior to the consumer test, the IRB (Institutional Review Board) of Auburn University approved the use of human panelists in this study (Exempt Protocol #19-437EX1910). The ice cream and carbonated beverage samples sweetened with different Rebaudioside treatments were evaluated by forty-one (n = 41) and thirty-nine (n = 39) naïve consumers, respectivelt. Two separate groups of panelists were invited to participate in the consumer evaluation of ice cream and carbonate beverages. Since stevia-sweetened food products tend to have a longer bitter aftertaste lingering in the mouth than traditional sucrose-made products, the consumer panel tasted the ice cream and carbonated beverages in two separate days so that sensory fatigue could be avoided as much as possible. Hence, a balanced incomplete block design was devised using RedJade® software (Redwood City, CA, USA) for the consumer research experimental design of both ice cream and carbonated beverage study so that the consumer panel could be asked to evaluate random samples masked with 3-digit codes throughout two consecutive days without any sensory fatigue caused by excessive repeated sample evaluation.

For ice cream consumer evaluation, around 30 g of ice cream was scooped into 2-oz souffle cups 24 hours before the testing and kept inside a –20°C walk-in freezer with their lids covered. As for the carbonated beverages, all treatments were made 24 hours prior to the evaluation, stored at airtight bottles, kept at ~4ºC refrigerator until consumer testing. Around 130 mL of the beverage samples were transferred in plastic cups immediately before consumer panel sample evaluation. Prior to actual sample evaluation, Simple Truth™ No Sugar-added Keto Low Carb vanilla ice cream (Kroger Co., Cincinnati, Ohio) and Diet Sam's Cola (Walmart Inc., Bentonville, AR) were used as blind-coded warm-up samples for the ice cream and carbonated beverage consumer testing, respectively. Then all treatments of ice cream and carbonated beverage were randomly presented to the panelists in the isolated sensory booths of Poultry Science sensory lab (Room 256A, 260 Lem Morrison Drive, Auburn, AL 36849) under normal color-masked lighting at around 22ºC room temperature away from any noise or distraction. In addition to ice cream and carbonated beverage samples, Great Value™ Unsalted Tops saltine crackers (Walmart Inc., Bentonville, Arkansas, USA) and DeerPark® spring water (Chesapeake, Virginia, USA) were also included in the trays as palate cleansers. The panelists were instructed to take 90 seconds rest between each sample evaluation for minimizing carryover effect. Then they were asked to evaluate their first impression of "overall liking" and "flavor liking" of the ice cream and carbonated beverage samples before swallowing on a 9-point hedonic scale (1=dislike extremely; 9=like extremely). After ingesting the samples, they were instructed to rate the samples' "overall liking" once again. In addition to these two liking questions, the panelists also judged "mouthfeel liking" only for the ice cream samples in similar manner as mentioned above.

2.9. Statistical Analysis

The data of descriptive analysis was collected using Compusense20 Cloud sensory analysis software (Compusense Inc., Guelph, Canada). RedJade® sensory evaluation software (Redwood City, CA, USA) was utilized to record the responses of the I panelists for the consumer evaluation of stevia-sweetened ice cream and carbonated beverages. AlphaSoft (version 2021-7.2.8, AlphaMOS, Toulouse, France) was used to compute the PCA of the e-tongue data to generate PCA plot of samples and PLSR to correlate human descriptive panel responses with e-tongue data. The discrimination among samples in the PCA plot was determined through their spread on the graph.

The DI (Discrimination Index) was also enumerated by grouping the samples' surface areas and displayed on top of the PCA plot to show how good or bad the e-tongue could distinguish the samples. The higher the DI is, the better the e-tongue's capability is to discriminate and group the samples based on their similarity. Results of descriptive analysis and consumer testing were expressed as mean ± SE (i.e., standard error) on a 15-cm line scale and 9-point hedonic scale, respectively. Finally, XLStat (AddinSoft, New York, NY, USA) was used to generate the PCA bi-plots and dendrograms of AHC (Agglomerative Hierarchical Clustering) as well as to determine significant differences among samples at $\alpha = 0.05$ significance level by employing one-way ANOVA (analysis of variance) with Tukey's HSD (Honestly Significant Difference) Test for post hoc analysis with 95% confidence level. Samples were considered to have a statistically significant difference at $P < 0.05$. For the AHC (Agglomerative Hierarchical Clustering) analysis, the distance of the cluster analysis was enumerated through the implementation of Euclidean method with the proximity type set on the dissimilarities of the samples. The Ward's method was used to cluster the agglomeration with the entropy selected for the truncation of the dendrogram. XLStat was also used to determine the relationship between the descriptive analysis data of different stevia blends evaluated by the trained panel and the consumer acceptance of ice cream and carbonated beverage judged by 82 naïve consumers on a 9-point hedonic scale with Jackknife (LOO) set as cross-validation method.

3. Results and Discussion

3.1. Iso-sweetness Levels of Stevia Blends

The results of the 2-AFC test for determining the iso-sweetness level of Reb A, D, and M equivalent to 9% sucrose solution is shown in Figure 2.2.

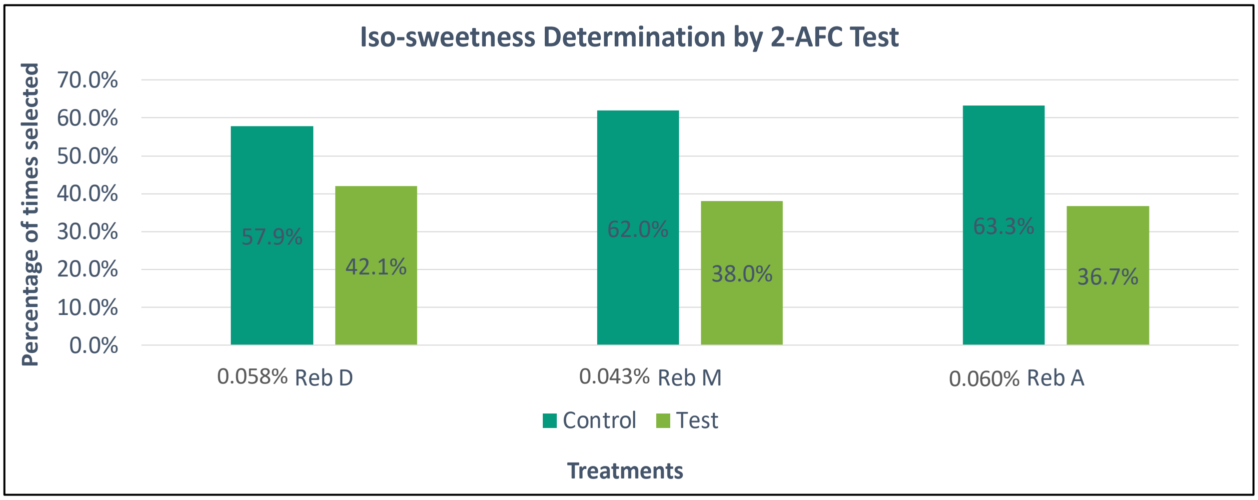

Figure 2.2. Iso-sweetness determination of Reb A, D, and M equivalent to 9% sucrose solution by 2-AFC test; Control= 9% sucrose solution; Test = steviol glycosides named below with iso-sweet concentration; No statistical difference (*P* < 0.05) between sucrose control and sweetener (i.e., iso-sweet).

As can be seen in Figure 2.2, the iso-sweet 0.058% Reb D was selected 42.1% of times while the control (9% sucrose solution) was selected 57.9% of times. In contrast, 0.043% Reb M and 0.060% Reb A were chosen 38% and 36.7% times as compared to their iso-sweet equivalent of the control (9% sucrose solution) preferred 62% and 63.3% of times, respectively, for these priorly mentioned steviol glycosides. No statistical difference was observed (*P* < 0.05) between 9% sucrose solution (control) and 0.060% Reb A, 0.058% Reb D, and 0.043% Reb M as per their percentage of times selected. In summary, the results of the 2-AFC test revealed that 0.060% Reb A, 0.058% Reb D, and 0.043% Reb M were found to have iso-sweetness concentration equivalent to 9% sucrose solution. For this reason, these iso-sweet concentrations determined from the 2-

AFCs on the individual Rebaudioside treatments namely 0.060% Reb A, 0.058% Reb D, and 0.043% Reb M with iso-sweetness equivalent to 9% sucrose solution were used to formulate 7 ratio blends mentioned as Ratio 1 to Ratio 7 in Table 2.

3.2. Descriptive Analysis of Stevia Blends

The ratings of six expert panelists on a 15-cm line scale for 13 different descriptive taste attributes are given in Table 2.6. No significant difference ($P > 0.05$) was observed among various Rebaudioside treatments as mentioned in Table 2.6 for different descriptive taste attributes of sweetness such as sweetness onset, sweet taste, as well as persisting sweet taste at 30 seconds, 60 seconds, 2 minutes, and 3 minutes. Although the sweetness onset of the treatments did not have any statistically significant difference ($P > 0.05$), Ratio 2 and Ratio 3 exhibited the slowest (3.68±0.15) and fastest (4.17±0.14) sweetness onset, respectively, among all treatments. As for the solo Rebaudiosides only, the slowest onset of sweetness was demonstrated by Reb A (3.90±0.12) whereas Reb D (4.17±0.09) has the fastest sweetness onset (4.17±0.14). However, the sweetness onset of Reb M (4.05±0.09) was very similar to that of Reb D (4.17±0.09) with Reb D scoring slightly higher in the descriptive analysis. Ratio 3 scored the highest rating for sweet taste (8.83±0.15) while Reb A received the lowest sweet taste score (8.42±0.25) with Reb D (8.72±0.18) rated comparatively higher among the solo Rebaudioside treatment for sweetness. Both at 30 and 60 seconds, the highest level of sweet taste was found in Reb D (2.79±0.15 at 30 seconds, 2.15±0.13 at 60 seconds) while Ratio 6 gained the lowest sweet taste rating (2.50±0.13 at 30 seconds; 1.78±0.13 at 60 seconds). The highest and lowest rating for sweet taste at 2 minutes were received by Reb D (1.37±0.16) and Reb A (1.18±0.14), respectively, whereas Ratio 1and Ratio 7 scored the highest (1.04±0.19) and lowest (0.71±0.18) sweet taste at 3 minutes, respectively.

In term of bitterness, Reb A exhibited the highest level of bitterness both in terms of "bitter taste" and lingering "bitter taste at 90 seconds" with 1.42±0.25 and 0.60±0.16 ratings from the expert descriptive panelists. Based on the rating intensities, a significant difference ($P < 0.05$) was observed for "bitter taste" between Reb A (1.42±0.25) and Reb D (0.08±0.06), with these two treatments scoring the highest and lowest bitterness, respectively. The bitter taste of Reb A (1.42±0.25) and Reb M (0.16±0.08) was also found to be significantly different ($P < 0.05$) albeit no significant difference between Reb D (0.08±0.06) and Reb M (0.16±0.08) for their bitterness. These results are consistent with the findings of Prakash et al. (2014) who reported less perceptible bitterness in Reb M than Reb A both in their respective water and acidified solutions (Prakash et al., 2014). Further, Tao & Cho (2020) made alike observations for the consumer evaluation of solo stevia solutions in which significantly higher ($P < 0.05$) 'in-mouth', 'immediate', and 'lingering' bitterness were perceived in Reb A aqueous solution than those of Reb D or M with no significant difference ($P < 0.05$) between Reb D and Reb M for these previously-stated bitter aftertaste attributes (Tao & Cho, 2020). Similar pattern was also observed for the expert panels' rating on "bitter taste at 90 seconds" taste attribute in which the bitterness of Reb A (0.60±0.16) was found to be significantly higher ($P < 0.05$) than all other Rebaudioside treatments after 90 seconds of evaluation. Likewise, Rebaudioside ratios containing higher percentage of Reb A namely Ratio 2, Ratio 3, and Ratio 7 were perceived to possess significantly higher bitterness ($P < 0.05$) through descriptive analysis with 0.57±0.12, 0.73±0.18, and 0.67±0.17 ratings, respectively, by the trained panel on 15-cm line scale. Comparatively higher intensities of sour taste, metallic, anise/licorice, astringence, and thickness were observed in Ratio 3 (0.22±0.17), Ratio 7 (0.23±0.10), Reb M (0.13±0.08), Ratio 6 (1.94±0.17), and Ratio 1 (1.03±0.10), respectively, although no significant difference ($P < 0.05$) existed between treatments for these descriptive characteristics (see Table 2.6).

Table 2.6. Expert panels' ratings of 13 descriptive taste attributes on a 15-cm line scale.

Descriptive taste attributes	Different stevia blends used in Descriptive Analysis									
	Reb A	Reb D	Reb M	Ratio 1	Ratio 2	Ratio 3	Ratio 4	Ratio 5	Ratio 6	Ratio 7
Sweetness onset	3.90±0.12	4.17±0.09	4.05±0.09	4.01±0.12	3.68±0.15	4.17±0.14	3.92±0.17	4.02±0.19	4.13±0.14	3.87±0.18
Sweet taste	8.42±0.25	8.72±0.18	8.55±0.18	8.76±0.14	8.68±0.13	8.83±0.15	8.81±0.12	8.72±0.18	8.74±0.16	8.46±0.18
Sweet taste at 30 s	2.52±0.18	2.79±0.15	2.73±0.16	2.65±0.15	2.64±0.18	2.53±0.12	2.71±0.16	2.57±0.12	2.50±0.13	2.51±0.18
Sweet taste at 60 s	1.98±0.12	2.15±0.13	1.91±0.15	2.01±0.11	1.91±0.12	1.89±0.12	2.01±0.17	1.88±0.11	1.78±0.13	1.78±0.15
Sweet taste at 2 min	1.18±0.14	1.37±0.16	1.24±0.17	1.52±0.16	1.26±0.17	1.19±0.16	1.40±0.17	1.34±0.14	1.25±0.17	1.18±0.18
Sweet taste at 3 min	0.84±0.15	0.86±0.19	0.95±0.19	1.04±0.19	0.89±0.17	0.94±0.19	0.91±0.17	0.87±0.16	0.83±0.17	0.71±0.18
Bitter taste	1.42±0.25^{A}	0.08±0.06^{D}	0.16±0.08^{CD}	0.29±0.12^{BCD}	0.57±0.12^{BCD}	0.73±0.18^{B}	0.33±0.15^{BCD}	0.33±0.13^{BCD}	0.25±0.13^{CD}	0.67±0.17^{B}
Bitter taste at 90 s	0.60±0.16^{A}	0.03±0.03^{B}	0.06±0.04^{B}	0.03±0.04^{B}	0.11±0.05^{B}	0.19±0.10^{B}	0.03±0.03^{B}	0.08±0.05^{B}	0.08±0.06^{B}	0.08±0.05^{B}
Sour taste	0.06±0.06	0.00±0.00	0.06±0.06	0.00±0.00	0.00±0.00	0.22±0.17	0.06±0.06	0.00±0.00	0.08±0.08	0.00±0.00
Metallic	0.16±0.08	0.08±0.06	0.03±0.03	0.15±0.09	0.08±0.05	0.08±0.06	0.11±0.06	0.14±0.05	0.06±0.06	0.23±0.10
Anise/licorice	0.07±0.07	0.06±0.06	0.13±0.08	0.06±0.04	0.03±0.03	0.08±0.06	0.03±0.03	0.11±0.08	0.06±0.04	0.06±0.06
Astringency	1.82±0.14	1.69±0.17	1.63±0.14	1.94±0.13	1.81±0.11	2.00±0.16	1.81±0.14	1.67±0.13	1.94±0.17	1.86±0.17
Thickness	0.83±0.11	0.89±0.10	0.88±0.10	1.03±0.10	0.94±0.08	0.94±0.08	0.89±0.10	0.89±0.10	0.92±0.08	0.94±0.08

^{A,B,C,D} Rows containing different superscripts indicate significant difference ($P < 0.05$);
Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively).
Ratio 1 = 33.4% of Reb A + 33.3% of Reb D + 33.3% of Reb M; Ratio 2 = 50.0% of Reb A + 50.0% of Reb M; Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 4 = 50.0% of Reb D + 50.0% of Reb M; Ratio 5 = 16.7% of Reb A + 16.7% of Reb D + 66.6% of Reb M; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

The principal component bi-plot shown in Figure 2.3 demonstrates the summarized overall relations among the stevia blends and their descriptive attributes. The first two principal components were able to describe 38.77% and 20.23% variations throughout the F1-axis and F2-axis, respectively, by accounting for a total of 58.99% explanation within the data variability of the descriptive attributes.

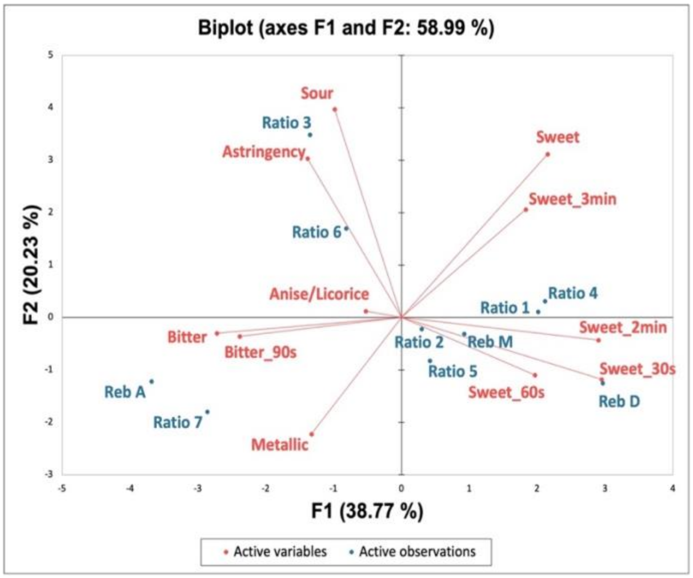

Figure 2.3. Principal component biplot of the descriptive analysis of taste attributes of different stevia blends. Each red dot represents the mean of descriptive taste attributes evaluated by a trained panel (*n* = 6) on a 15-cm line scale; each blue dot indicates the stevia blends.

Reb D and Reb M showed similar descriptive taste profiles whereas Reb A was distinctly different from these two Rebaudiosides based on their descriptive sensory scores across the negative F2-axis in the PCA bi-plot (see Figure 2.3). The descriptive taste attributes of Reb D, Reb M, Ratio 2, and Ratio 5 were associated with sweet taste at 30 seconds, 60 seconds, and 2 minutes, respectively. In contrast, bitter taste, bitterness at 90 seconds, and metallic attributes were related to Reb A and Ratio 7, whereas Ratio 3 and Ratio 6 were characterized with astringency, sour, and anise/licorice taste. Ratio 1 and Ratio 4 were loosely associated with sweetness at 3 minutes and sweet taste based on their placement in the positive F1 axis.

Figure 2.4 illustrates the AHC dendrogram of all samples for their respective descriptive analysis. All the stevia blends were categorized into five separate clusters distinct from each other based on their descriptive panel ratings of different taste attributes. As demonstrated in Figure 2.4, Ratio 1, Ratio 2, and Ratio 4 formed the first cluster denoted as C1 in the AHC Dendrogram followed by Ratio 3 and Ratio 6 as the second cluster C2 (see Figure 2.4B). The third cluster C3 consisted of Reb D, Reb M, and Ratio 5 whereas Ratio 7 and Reb A were the sole members of the fourth cluster (C4) and fifth cluster (C5), respectively. These clustering of blends are consistent with PCA results (Figure 2.3) in which Reb D, Reb M, and Ratio 5 were closely located to sweet taste at 30 s, 60 s, and 2 minutes potentially resulting these blends to form C3 cluster, whereas proximity of Ratio 3 and Ratio 6 towards sour, astringency, anise/licorice may have factored into their formation of C2 cluster. In contrast, Reb A was placed near bitter taste and bitter taste at 90 s while Ratio 7 was remotely associated with metallic, thus, forming two separate clusters C4 and C5, respectively. All the other blends namely Ratio 1, Ratio 2, and Ratio 4 did not follow through any particular taste attribute in the PCA bi-plot which is why they may have been grouped together into the first C1 cluster.

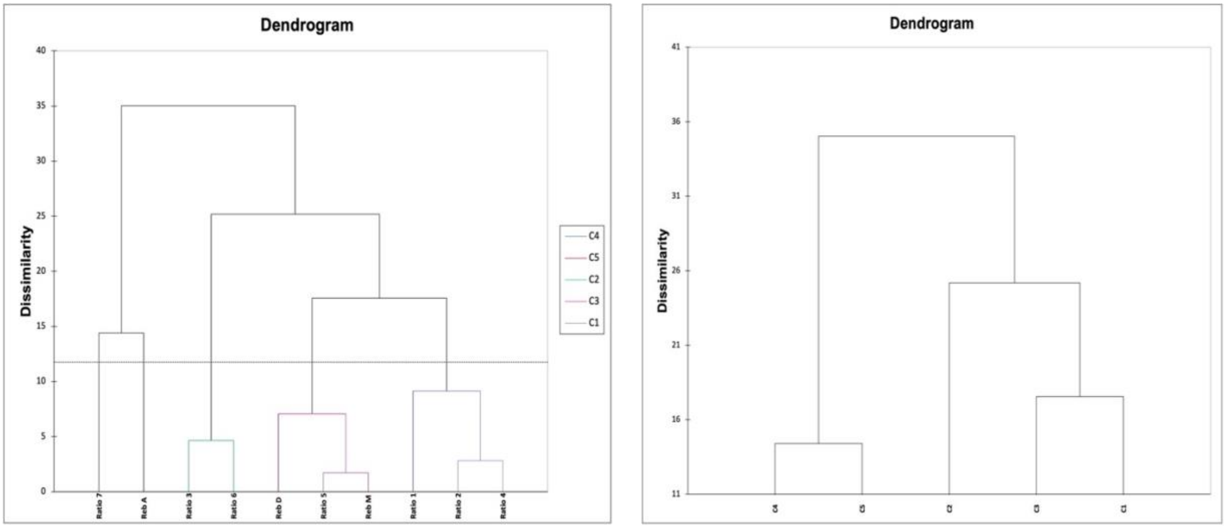

Figure 2.4. Dendrogram of Agglomerative Hierarchical Clustering (AHC) for the of descriptive taste attributes of different Stevia blends.

3.3. E-tongue Analysis of Stevia Blends

The stevia blends as mentioned in Table 2.2 were analyzed in the e-tongue to understand its potential to discriminate the samples based on their blend ratios of different Rebaudiosides. The taste map of different stevia blends generated as a PCA plot of the corresponding e-tongue analysis has been demonstrated in Figure 2.5. As it is evident from Figure 2.5, the first two principal components of the PCA could explain 52.72% and 32.32% of the variations of the e-tongue responses for different stevia blends across the first principal component (PC1) and second principal component (PC2). Therefore, a total of 85.04% variations of the e-tongue data could be explained by the PCA. Also, the PCA plot had a DI of 89 with distinct groups of different stevia blends that did not overlap each other. Reb A, Reb D, and Reb M were clearly opposed to each other maintaining distinct distance in their placement within the PCA plot. Ratio 3, Ratio 4, Ratio 5, and Ratio 6 appeared to be placed closely together whereas Ratio 1, Ratio 2, and Ratio 7 were closer to Reb M as compared to all other treatments. These results mean that the e-tongue had the capacity of discriminating different stevia blends with varying ratios of different Rebaudiosides.

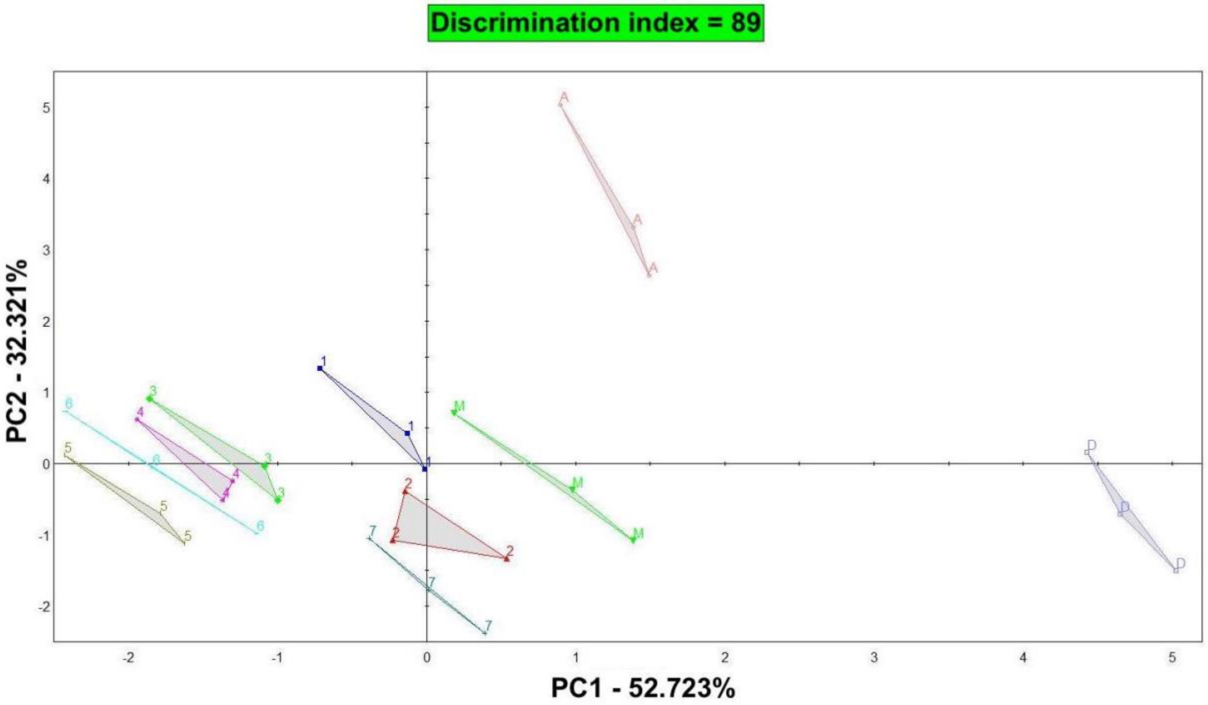

Figure 2.5. PCA Plot indicating the discrimination of different stevia blends by the e-tongue.

The discrimination power of the AHS, CTS, NMS, PKS, CPS, ANS, and SCS sensors included in the #6 sensor array of the Astree e-tongue along with their %RSD for the analysis of all stevia blends are represented in Table 2.7. The reproducibility and precision of the e-tongue analysis are interpreted by the "discrimination power" and %RSD (Relative Standard Deviation) of the sensors to determine the reliability and acceptability of the data. Each sensors' capacity to discriminate samples based on their chemical variations in the liquid matrix is denoted by the term "discrimination power" that ranges from 0 to 1, with values closer to 1 indicating superior performance when it comes to sample discrimination. However, a discrimination power less than 0.50 is indicative of the sensor's poor discrimination capability (Muenprasitivej, 2022). As given in Table 2.7, all the sensors exhibited satisfactory discrimination power (more than 0.60) to distinguish all stevia blends based on their varying proportions of Reb A, D, and M.

Table 2.7. The discrimination power and relative standard deviation (%RSD) of Astree e-tongue sensors for the discrimination of different stevia blends.

Sensors	Discrimination Power	%RSD of E-tongue Sensors									
		Reb A	Reb D	Reb M	Ratio 1	Ratio 2	Ratio 3	Ratio 4	Ratio 5	Ratio 6	Ratio 7
AHS	0.951	0.333	0.310	0.599	0.400	0.393	0.527	0.466	0.486	0.617	0.351
PKS	0.940	1.224	0.581	1.108	0.787	0.621	0.829	0.663	0.861	1.188	0.794
CTS	0.834	1.102	0.431	0.544	0.400	0.332	0.467	0.321	0.351	0.620	0.357
NMS	0.845	0.341	0.697	0.895	0.741	0.521	0.724	0.710	0.741	0.895	0.814
CPS	0.679	1.432	1.350	1.318	1.108	0.808	1.044	0.957	0.944	1.125	0.858
ANS	0.870	0.511	0.756	0.520	0.757	0.791	0.511	0.712	0.509	0.404	0.459
SCS	0.990	0.386	0.033	0.196	0.086	0.608	0.135	0.263	0.144	0.257	0.181

Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively). Ratio 1 = 33.4% of Reb A + 33.3% of Reb D + 33.3% of Reb M; Ratio 2 = 50.0% of Reb A + 50.0% of Reb M; Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 4 = 50.0% of Reb D + 50.0% of Reb M; Ratio 5 = 16.7% of Reb A + 16.7% of Reb D + 66.6% of Reb M; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

The precision of e-tongue analysis can be understood by %RSD as evaluated through the division of the STD (Standard Deviation) by the mean of each sensor intensity with subsequent multiplication of 100 [%RSD=(STD/Mean)×100]. The data of the e-tongue analysis is regarded to have good precision when the %RSD of the e-tongue sensors fall within 5% or less (Tao, 2020). The lower is the %RSD, the higher is the analytical precision of a specific sensor for a particular analysis – and vice versa (Zheng & Keeney, 2006). As shown in Table 2.4, the highest %RSD of all the sensors ranged from 0.60% to 1.40%, whereas their lowest were within the range of 0.033–0.808%. These results indicate that all the sensors of the e-tongue could analyze and discriminate the different stevia blends very precisely considering the fact that the highest %RSD among all sensors were found to be only 1.432% (CPS sensor) which is considerably less than the maximum acceptable %RSD value of 5%.

The AHC dendrogram for the e-tongue analysis of different stevia blends are shown in Figure 2.6. Based on their e-tongue responses, Ratio 1, Ratio 3, Ratio 4, Ratio 5, and Ratio 6 formed a distinct C1 cluster, whereas Reb M, Ratio 2, and Ratio 7 were grouped into C2 cluster. Additionally, Reb A and Reb D were separated into two different clusters indicated as C3 and C4, respectively. The reason that Reb A and Reb D were the only members of two different clusters separated from the rest of the stevia blends may be attributed to the prevalent bitter aftertaste typical of Reb A and D. These two steviol glycosides (Reb A and D) are known to impart a bitterness sensation that lingers in the mouth longer than Reb M. This happens because Reb M possess more glycosidic bonds in its chemical structure than Reb A and D which is thought to induce more sweetness in Reb M solutions than the others. Due to this, the e-tongue sensors may have sensed chemical variations in the Reb A and Reb D solutions that were seemingly different than the other blends, resulting the formation of two separate groups for these two Rebaudiosides (Reb A and Reb D).

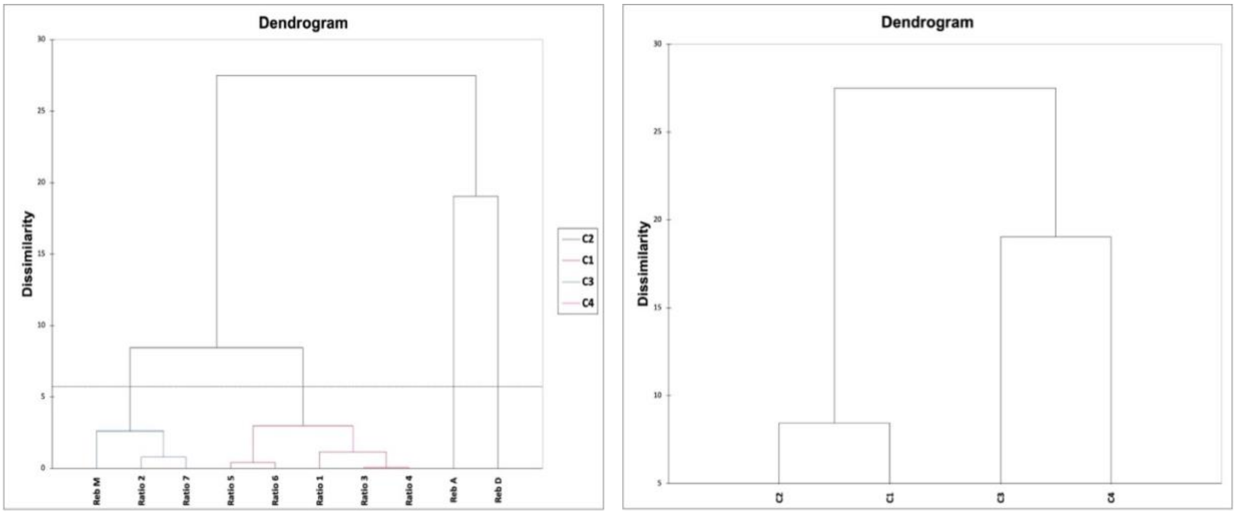

Figure 2.6. Dendrogram of Agglomerative Hierarchical Clustering (AHC) for the e-tongue analysis of different stevia blends.

These results are in line with the findings previously reported by Muenprasitivej (2022) and Tao (2020) who differentiated the flavor profiles of stevia solutions with satisfactory DI using the same α-Astree e-tongue used in this current study. However, iso-sweetness levels of Reb A, D, and M with 9% sucrose equivalance was maintained in this study whereas both Muenprasitivej (2022) and Tao (2020) matched the sweetness concentration of Reb M (0.1% w/v) to 14% sucrose (w/v) and then used the same concentrations of Reb D and M as Reb M, which may have caused slight differences in discriminations on the PCA taste map due to the bitterness of stevia blends despite isosweetness levels of Reb A, D, and M with different concentrations. Further, the %RSD and discrimination power of e-tongue analysis of both Muenprasitivej (2022) and Tao (2020) are similar to the values observed for these parameters in the present investigation which indicates the capability of α-ASTREE e-tongue to discriminate stevia blends with varying Reb ratios. In another study, the α-ASTREE II e-tongue (Alpha MOS) was successfully implemented to discriminate different sweetener blends containing varying ratios of stevia (3.19% Reb A *w/w*), coconut sugar, and agave with a total of 92.6% variability explained by PCA. Based on these findings, it is reasonable to infer that the e-tongue can be a viable analytical tool to screen different stevia blends of varying Rebaudioside ratios based on all the findings and data discussed above.

3.4. Relationship between E-tongue Data and Descriptive Analysis

The data obtained from e-tongue analysis was subsequently correlated with the descriptive analysis of 12 taste attributes evaluated by the expert trained panel (*n* = 6) on a 15-cm line scale for different stevia blends through PLSR to determine their relationship. The “thickness” descriptive taste attribute was excluded from the PLSR model building since it is more of a viscous mouthful sensation rather than being a solely taste attribute. The parameters of PLSR correlation between the e-tongue responses and the descriptive analysis of all taste attributes except “thickness” are given in Table 2.8.

Table 2.8. Parameters of PLSR correlation between e-tongue data and descriptive analysis.

Attributes	R^2 (PLSR Correlation Coefficient)
Sweetness onset	0.1427
Sweet taste	0.3025
Sweet taste at 30 seconds	0.4065
Sweet taste at 60 seconds	0.455
Sweet taste at 2 minutes	0.1845
Sweet taste at 3 minutes	0.1426
Bitter taste	0.4956
Bitter taste at 90 seconds*	0.9116
Sour taste	0.1596
Astringency	0.2487
Anise/licorice	0.1048
Metallic	0.08081

* indicates $P < 0.05$

The PLSR correlation coefficient R^2 to associate the e-tongue responses with the expert panel ratings of “bitter taste at 90 seconds” taste attribute was determined to be 0.9116 with a *P*-value of 0.023, accounting for 91.16% variability within the PLSR model. The PLSR calibration curve correlating the e-tongue data with the expert panel rating of “bitter taste at 90 seconds” taste attribute on a 15-cm line scale is shown in Figure 2.7.

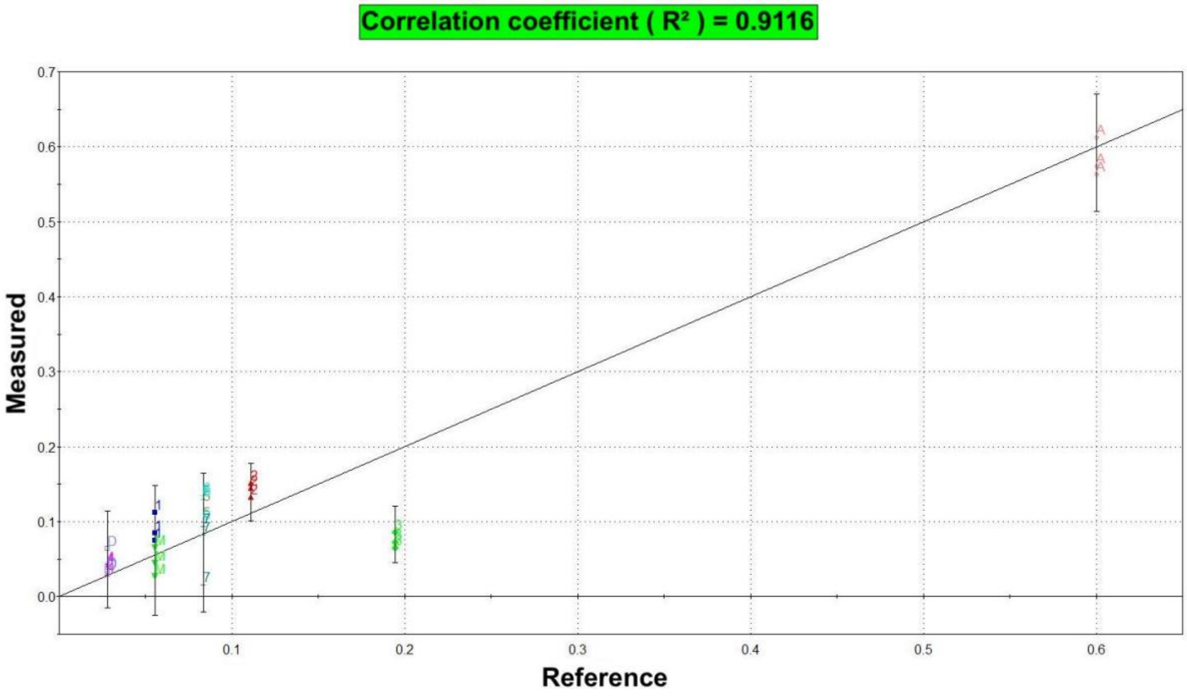

Figure 2.7. PLSR Calibration curve to correlate the e-tongue data with expert panel rating of "bitter taste at 90 seconds" descriptive taste attribute.

Such a high R^2 value (= 0.9116) with $P < 0.05$ significance indicates the high strength of correlation between the e-tongue data and sensory scores of "bitter taste at 90 seconds" taste attribute. In summary, the findings mentioned above point out that there is a high correlation between the 15-cm line scale rating evaluated by the expert panel for "bitter taste at 90 seconds" and the e-tongue data of the stevia blends used in this current study. The PLSR for all other descriptive taste attributes with the e-tongue data had R^2 values less than 0.50, indicating that the models were not validated and fitted properly to explain any correlation. These results mean that the e-tongue has the potential of predicting the bitter taste of unknown samples at 90 seconds due to its strong correlation to the trained panel data evaluated for this descriptive taste attribute. Hence, it is possible to use e-tongue to screen sweeteners based on their bitterness at 90 seconds and formulate proper substitute of sweetener blend as a sugar reduction strategy. These PLSR results also point out to the fact that the “bitter taste at 90 seconds” descriptive taste attribute is a viable sensory descriptor of stevia blends. Similar studies conducted by Lorenz et al. (2009), Kirsanov et al. (2012), Waldrop and Ross (2014), Newman et al. (2015) have also reported high correlation between e-tongue analysis and expert panel data of different food products highlighting e-tongue’s relevance as a sensory instrument, meaning that e-tongue can be used either in conjunction with or as a replacement of descriptive analysis for the discrimination and screening of stevia blends based on selective taste attributes such as bitter aftertaste.

3.5. Selection of Stevia Blends for Ice Cream and Carbonated Beverage Formulation

Among all the stevia blends, Ratio 3, Ratio 6, and Ratio 7 were chosen to be used for sweetening the ice creams and carbonated beverages that were subsequently formulated for consumer acceptance. These blends were selected over other ratios because significantly different ($P < 0.05$) bitter taste was perceived in Ratio 3, Ratio 6, and Ratio 7 with descriptive panel liking scores of 0.73±0.18, 0.25±0.13, and 0.67±0.17, respectively (Table 2.6). Besides, Ratio 3 exhibited fastest sweetness onset (4.17±0.14) and highest bitter taste (0.73±0.18), whereas Ratio 6 had lowest bitter score (0.25±0.13) with relatively faster onset of sweetness (4.13±0.14) than other blends. Also, Ratio 7 scored the relatively slower sweetness onset (3.87±0.18) in addition to significantly higher ($P < 0.05$) bitter taste (0.67±0.17) among all stevia blends. For these reasons, Ratio 3, 6, and 7 along with Reb A, D, and M were utilized in the formulation of ice cream and carbonated beverage for consumer testing.

3.6. Consumer Acceptance of Ice Cream and Carbonated Beverages

The consumer acceptance of ice cream formulated using different stevia blends and rated by 41 naïve consumers on a 9-point hedonic scale is given in Table 2.9. The consumers rated the ice cream samples for four sensory attributes namely overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel, whereas the carbonated beverages were evaluated for the same attributes except mouthfeel. As mentioned in Table 2.9, the ice cream samples sweetened with Reb M was rated as 5.62±0.36, 5.52±0.37, 5.62±0.35, and 6.10±0.29 for overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel sensory attributes on a 9-point hedonic scale, which was significantly higher ($P < 0.05$) than the other samples for the same attributes. These results mean that Reb M ice cream was "neither liked nor disliked" for its overall liking (before swallowing) (5.62±0.36), overall liking (after ingestion) (5.52±0.37), and flavor (5.62±0.35). However, its mouthfeel (6.10±0.29) was graded as "slightly liked" through the consumer evaluation. Subsequently, the second highest rating for all the taste attributes was attained by ice cream samples formulated using Ratio 6 with overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel of 5.12±0.33, 5.07±0.32, 4.88±0.33, and 5.12±0.29 on a 9-point Hedonic scale, respectively, indicating that this ice cream sample was "neither liked nor disliked" for overall liking (both before and after ingestion) and mouthfeel while "slightly disliked" in terms of flavor. Having the lowest sensory scores, Reb A sweetened ice cream samples were evaluated to have 4.45±0.35, 4.00±0.35, 4.45±0.36, and 4.79±0.32 for overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel, respectively. In brief, the ice cream samples prepared with Reb M and Ratio 6 achieved significantly higher ($P < 0.05$) 9-point Hedonic scale ratings than Reb A-made ice creams for overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel.

Table 2.9. The consumer acceptance (*n* = 41) of different ice cream samples formulated with different stevia blends expressed as mean±SE of different liking attributes.

Ice cream samples	Consumer liking scores on 9-point Hedonic scale			
	Overall liking (before swallowing)	Overall liking (after ingestion)	Flavor	Mouthfeel
Reb A	4.45±0.35^{b}	4.00±0.35^{c}	4.45±0.36^{b}	4.79±0.32^{b}
Reb D	4.81±0.29^{ab}	4.62±0.30^{abc}	4.88±0.30^{ab}	4.95±0.30^{b}
Reb M	5.62±0.36^{a}	5.52±0.37^{a}	5.62±0.35^{a}	6.10±0.29^{a}
Ratio 3	4.88±0.29^{ab}	4.38±0.31^{bc}	4.60±0.30^{b}	4.52±0.29^{b}
Ratio 6	5.12±0.33^{ab}	5.07±0.32^{ab}	4.88±0.33^{ab}	5.12±0.29^{b}
Ratio 7	5.00±0.34^{ab}	4.76±0.31^{abc}	4.79±0.34^{ab}	5.07±0.30^{b}

^{abc} Columns containing different superscripts indicate significant difference ($P < 0.05$).
Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively).
Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

The fact that Reb M made ice cream formulated in this current research showed better consumer likability than those made of all other stevia blends are in agreement with the findings previously reported by Muenprasitivej et al. (2022) who reported Reb M ice cream were liked significantly higher ($P < 0.05$) for its sensory acceptance of 92 naïve consumers ($n = 92$). However, the 9-point Hedonic scale ratings for the overall liking (before swallowing: 5.62±0.36; after ingestion: 5.52±0.37), flavor (5.62±0.35), and mouthfeel (6.10±0.29) of the Reb M ice cream prepared in this study were relatively lower than that of Muenprasitivej et al. (2022) for its overall liking (7.1±0.13), flavor (6.5±0.19), and mouthfeel (6.7±0.14). However, less concentration of Reb A, D, and M (up to 0.06%) was used in this study to maintain 9% sucrose iso-sweet equivalence whereas Muenprasitivej et al. (2022) utilized 0.09% of solo Reb treatments with iso-sweet level of 14% sucrose, which might have promoted higher sweetness intensities perceived in their ice creams as compared to those formulated in this current study. In other words, this difference in consumer sensory liking scores may have occurred due to the different Reb M concentration used in these two studies for their respective ice cream formulation. To be specific, almost two times higher Reb M concentration (0.09% *w/v*) used by Muenprasitivej et al. (2022) in their ice cream preparation as compared to that of the current study (0.043% Reb M w/v) may have developed higher sweetness in their ice cream to garner more preferrable Hedonic impression with higher liking scores rewarded by the consumers.

In recent years, a considerable amount of research has investigated the effect of stevia use on the sensory acceptance of ice cream mainly due to the shift in the food industry to commercializing more reduced-sugar products with lower calories because of increasing consumer demand for such lower-calorie food items. Previously, ice cream formulated with 7% stevia (Gençdağ et al., 2021), 14.65% stevia (Ahmed et al., 2023), and 1.5% of Reb A (Velotto et al., 2021) resulted in satisfactory liking scores by human sensory panels. Although all of these studies have validated the use of stevia use in ice cream, its bitter aftertaste may potentially pose an issue to consumer preference. As a viable alternative to the bitterness problem, the applications of solo Reb D and M have improved the consumer sensory acceptance of ice cream to a greater extent (Muenprasitivej et al., 2022). However, ice cream produced with solo Reb D and M may incur notably higher production costs which may come to be a potential issue to the frozen dairy industry. Therefore, the blending strategy of Reb A, D, and M as postulated in this study may be a practical approach to mask the lingering bitter sensation in ice cream by being a viable alternative to Reb A and its associated sensory unpleasantness in frozen dairy applications.

The evaluation of consumer acceptability through a consumer panel of 39 people for carbonated beverages sweetened with different stevia blends are mentioned in Table 2.10. The carbonated beverage sample made of Ratio 7 was found to have the highest 9-point Hedonic scores for overall liking (before swallowing) (3.90±0.28), overall liking (after ingestion) (3.85±0.30), and flavor (3.92±0.30) sensory attributes. In comparison, Reb M made carbonated beverage sample had the lowest likability for all attributes and its 9-point Hedonic scale rating of overall liking (before swallowing), overall liking (after ingestion), and flavor were found to be 3.03±0.28, 3.05±0.28, and 2.85±0.28, respectively. While a significant different ($P < 0.05$) existed for the 9-point Hedonic scores of overall liking (before swallowing) and flavor between Ratio 7 and Reb M, no significant difference ($P < 0.05$) was observed among the six different carbonated beverage samples for their respective 9-point Hedonic scale ratings of overall liking (after ingestion) sensory attribute. Based on the 9-point Hedonic scale ratings of the consumer panel for all sensory attributes, it can be said that all the carbonated beverage samples were "moderately disliked" for all the sensory attributes investigated namely overall liking (before swallowing), overall liking (after ingestion), and flavor since all the Hedonic scale ratings were given the fact that the range of 3.03±0.28–3.92±0.30.

Table 2.10. The consumer acceptance ($n = 39$) of different carbonated beverages formulated with different stevia ratios expressed as mean±SE of different liking attributes.

Carbonate beverage samples	Consumer liking scores on 9-point Hedonic scale		
	Overall liking (before swallowing)	Overall liking (after ingestion)	Flavor
Reb A	3.44 ± 0.25^{ab}	3.18±0.22	3.26 ± 0.25^{ab}
Reb D	3.54 ± 0.27^{ab}	3.31±0.25	3.33 ± 0.25^{ab}
Reb M	3.03 ± 0.28^{b}	3.05±0.28	2.85 ± 0.28^{b}
Ratio 3	3.37 ± 0.23^{ab}	3.03±0.20	3.26 ± 0.22^{ab}
Ratio 6	3.85 ± 0.32^{ab}	3.72±0.30	3.64 ± 0.30^{ab}
Ratio 7	3.90 ± 0.28^{a}	3.85±0.30	3.92 ± 0.30^{a}

^{abc} Columns containing different superscripts indicate significant difference ($P < 0.05$).
Reb A, D, and M used in this study were prepared at iso-sweet levels to 9% sucrose (0.060%, 0.058%, and 0.043%, respectively). Ratio 3 = 50.0% of Reb A + 50.0% of Reb D; Ratio 6 = 16.7% of Reb A + 66.7% of Reb D + 16.6% of Reb M; Ratio 7 = 66.7% of Reb A + 16.7% of Reb D + 16.6% of Reb M.

Considering the simple food matrix of carbonated beverages, the bitter aftertaste of stevia blends may have been exposed to be more prominent by the consumers in their sensory characteristics, thus, resulting in lower sensory scores on a 9-point Hedonic scale. Further, these lower liking scores may have been the result of the panelist's disfavor of the syrup flavor that may have potentially skewed the consumer likings in the solo Reb treatments (i.e., Reb A, D, and M) as well as in the subsequent blend treatments (Ratio 3, Ratio 6, Ratio 7). Among the solo Reb treatments of the carbonated beverage samples namely Reb A, Reb D, and Reb M, the bitterness of Reb A may have been masked by the syrup and thus skewing the consumer acceptance in its favor as compared to Reb M.

3.7. Relationship between Descriptive Analysis and Consumer Liking Scores

PLSR analysis was conducted to investigate the correlation between the descriptive analysis of different stevia ratios and consumer acceptance of different ice cream and carbonated beverage samples sweetened with different stevia blends. The correlation loading plot for the PLSR between the stevia blends' descriptive analysis and ice cream consumer acceptance is depicted in Figure 2.8.

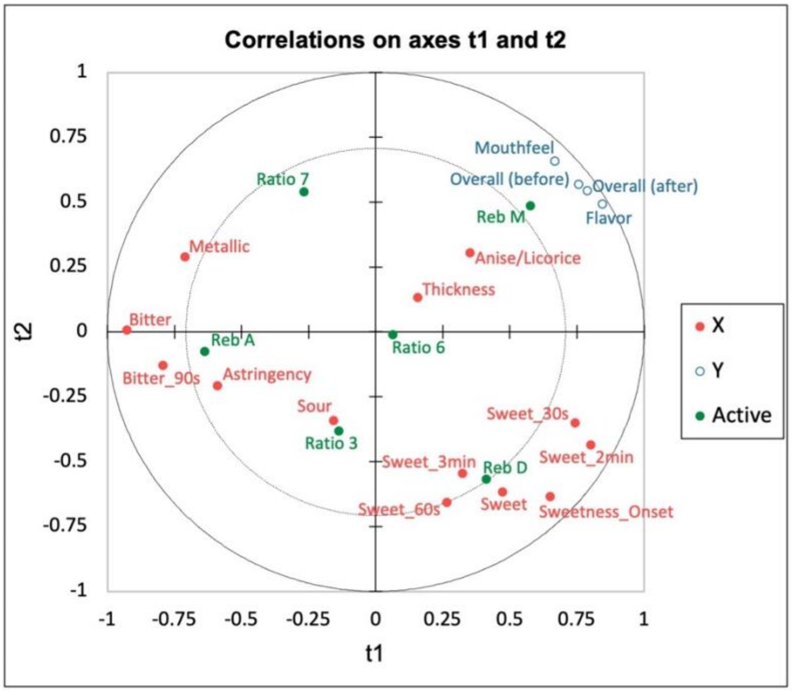

Figure 2.8. Correlation loading plot of PLSR between the descriptive analysis of stevia blends and consumer acceptance of ice cream.

The inner and outer ellipse of the PLSR correlation loading plots as depicted in Figure 2.8 and Figure 2.9 represent r = 0.75 and r = 1 that explains 75% and 100% of the variance, respectively. All the four sensory attributes evaluated by the consumers (overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel), seven descriptive analysis attributes (sweetness onset, sweet taste, sweet taste at 30 seconds, sweet taste at 2 minutes, bitter taste, bitter taste at 90 seconds, metallic), and one ice cream sample (Reb M) were located between the inner ellipse (r = 0.75) and outer ellipse (r = 1), respectively, which means that the PLSR model was able to well-explain these variables (0.75 < r < 1). As it is demonstrated in Figure 2.8, Reb M ice cream was associated with overall liking (before swallowing), overall liking (after ingestion), flavor, and mouthfeel attributes evaluated by the consumers, whereas Reb D ice cream was closely plotted around all the descriptive attributes related to sweetness (sweet taste, sweet taste at 30 seconds, sweet taste at 60 seconds, sweet taste at 2 minutes, sweet taste at 3 minutes, and sweetness onset). In contrast, Reb A ice cream was related to bitter taste, bitter taste at 90 seconds, and astringency. The placement of ice cream made of Ratio 6 was observed towards the middle of the correlation loading plot which indicates that its corresponding stevia blend (16.7% Reb A + 66.7% Reb D + 16.6% Reb M) may have induced a combined taste profile of Reb A, D, and M fused altogether inside the food matrix of Ratio 6 ice cream. These findings are consistent with the results of descriptive analysis and consumer evaluation data. The PLSR analysis revealed a moderate positive association (0.40 < r < 0.60) between the "sweet taste at 30 seconds" and ice cream "flavor" (r = 0.461), and also between "sweet taste at 2 minutes" and "flavor" (0.441). "Anise/ licorice" descriptive attribute had a strong positive association (0.60 < r < 0.80) with the "flavor" (r = 0.603) and a moderate positive association with the "overall liking (before swallowing)" (r = 0.558) and "mouthfeel" (r = 0.585) of the ice cream samples. These results indicate that the "flavor" of the ice cream samples increases with an increase in the "sweet taste at 30 seconds", "sweet taste at 2 minutes", and "anise/ licorice" descriptive taste attributes of the stevia blends.

However, a strong negative association (-0.60 < r < -0.80) existed between the "bitter taste" of the blends and the "overall liking (before swallowing)" (r = -0.704), "overall liking (after ingestion)" (r = -0.787), and "flavor" (r = -0.708) of ice cream. "Bitter taste at 90 seconds" was also had a strong negative association with the “overall liking (before swallowing)” (r = -0.700), “overall liking (after ingestion)” (r = -0.747), and “flavor” (r = -0.611). Similarly, “astringency” exhibited a strong negative association with “flavor” (r = -0.670) and “mouthfeel” (r = -0.704) of the ice cream samples. These findings mean that the “overall liking (before swallowing)”, “overall liking (after ingestion)”, and “flavor” of the ice cream samples are negatively affected when there is an increase of “bitter taste” and “bitter taste at 90 seconds” in the stevia blends. Also, there is a decrease in the “flavor” and “mouthfeel” of the ice creams when the “astringency” of the stevia blends increases.

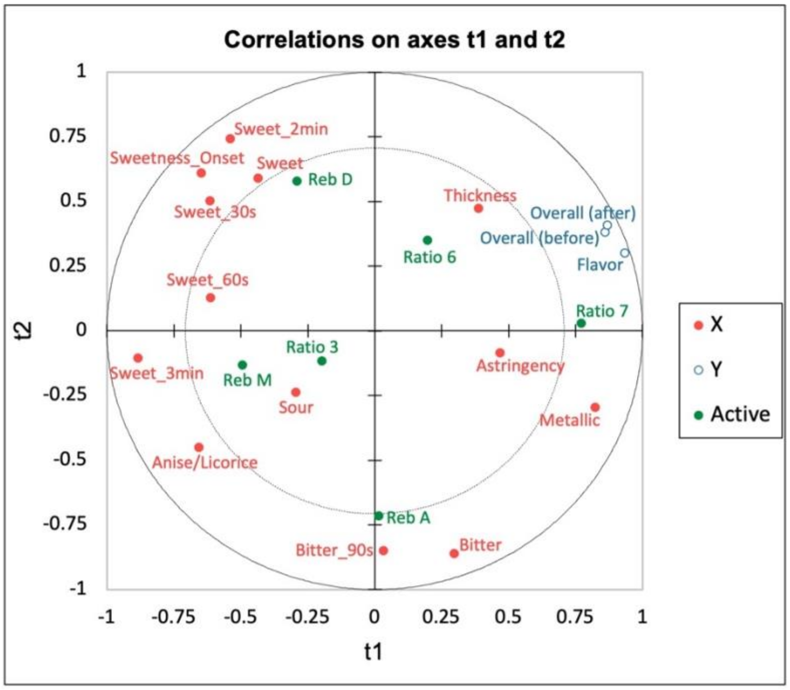

Figure 2.9. Correlation loading plot of PLSR between the descriptive analysis of stevia blends and consumer acceptance of carbonated beverage.

Figure 2.9 represents the correlation loading plot for the PLSR between the descriptive analysis of stevia blends and the consumer ratings of carbonated beverages. It is clear from Figure 2.9 that the carbonated beverage formulated with Ratio 7 was closely associated with the consumer ratings for overall liking (before swallowing), overall liking (after ingestion), and flavor, whereas Reb D sweetened carbonated beverage showed close association with sweet taste, sweet taste at 30 seconds, sweet taste at 2 minutes, and sweetness onset descriptive attributes. In comparison, Reb A made carbonated beverage was plotted around bitter taste and bitter taste at 90 seconds. The consumer ratings of all sensory attributes (overall liking (before swallowing), overall liking (after ingestion), flavor) along with nine descriptive taste attributes of stevia blends (sweetness onset, sweet taste, sweet taste at 30 seconds, sweet taste at 2 minutes, sweet taste at 3 minutes, bitter taste, bitter taste at 90 seconds, anise/ licorice, metallic) along with one carbonated beverage sample (Ratio 7) fell between the inner and outer ellipse of the correlation loading plot as depicted in Figure 2.9, indicating well-explanation of these variables by the PLS regression model ($0.75 < r < 1$).

The results of the PLSR correlation suggested a moderate positive association ($0.40 < r < 0.60$) between the metallic descriptive attribute of the stevia blends and the consumers' liking for overall liking (before swallowing) ($r = 0.567$), overall liking (after ingestion) ($r = 0.519$), and flavor ($r = 0.689$) of the carbonated beverage. A moderate positive association was also observed between the astringency of the stevia blends and the overall liking (before swallowing) ($r = 0.511$) and flavor ($r = 0.527$) of the carbonated beverage. However, the anise/ licorice taste of the stevia blends had a strong negative association ($-0.60 < r < -0.80$) with all the consumer acceptance attributes of the carbonated beverage namely overall liking (before swallowing) ($r = -0.915$), overall liking (after ingestion) ($r = -0.749$), and flavor ($r = -0.846$). These finding indicate that the overall liking (before swallowing, overall liking (after ingestion), and flavor of the carbonated beverage increase with an increase in the descriptive analysis rating in the metallic and astringency of the stevia blends. Also, all the consumer liking attributes (overall liking (before swallowing, overall liking (after ingestion), and flavor) will decrease if there is an increase of anise/ licorice taste in the descriptive rating for the stevia blends.

4. Conclusion

The effect of blending Reb A, D, and M to improve their flavor profiles and enhance consumer likability in two food applications was studied in this investigation along with the e-tongue's potential to discriminate the blends. According to the descriptive analysis evaluated by the trained panel ($n = 6$) for different stevia blends, no significant difference ($P < 0.05$) existed among the stevia blends for all descriptive taste attributes except "bitter taste" and "bitter taste at 90 seconds". Reb D, Reb M, and Ratio 6 (66.7% Reb D) had comparatively lower bitter taste although no significant difference ($P < 0.05$) existed between Ratio 6 and Reb M for this attribute. As for the "bitter taste at 90 seconds", Reb A had significantly higher bitterness ($P < 0.05$) than all other blends. These descriptive analysis data of various stevia blends help understand the effect of blending on the sensory profiles of stevia solutions, especially the changes in the bitter aftertaste, which is often an undesirable sensory characteristic of stevia-sweetened products. The PCA bi-plot of the descriptive analysis suggested that Reb D was associated with sweet taste at 30 seconds while Reb A and Ratio 7 (66.7% Reb A) were located nearby bitter taste, bitter taste at 90 seconds, and metallic taste attributes. The PCA of e-tongue data revealed its potential of discriminating all the stevia blends with high DI (= 89) and 85.04% explanation of total variability. In addition, the e-tongue analysis was highly associated ($R^2 = 0.9116$) with the "bitter taste at 90 seconds" through PLSR. It means that the e-tongue can be a useful sensory instrument in the food and beverage industry to screen stevia blends based on their bitter aftertaste that lingers through 90 seconds to save the time and resources usually required for trained panel evaluation. Also, this high correlation between the electronic tongue analysis with human descriptive data points out its discrimination potential in screening various stevia blends. The consumer research of food products developed using the stevia blends showed better consumer acceptance of ice cream formulated with Reb M and Ratio 6, whereas Ratio 7 sweetened carbonated beverages received relatively higher consumer liking scores. The PLSR correlation between the descriptive analysis of stevia blends and consumer acceptance of ice cream and carbonated beverage prepared from these stevia blends revealed that the consumer likings of these stevia-sweetened products were associated with some descriptive taste attributes. The consumer acceptance of stevia-sweetened ice cream and carbonated beverage provides insight on how changing the ratios of Reb A, D, and M impact the sensory likability of stevia-formulated food items. Information contained in this investigation may prove to be useful for the sweetener and food industry to mask the bitter aftertaste of stevia in food applications through blending strategy.

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CHAPTER 3. CORRELATION BETWEEN ELECTRONIC SENSES AND SENSORY ANALYSIS OF STRAWBERRIES AND BLUEBERRIES

Abstract

Although flavor characterization of many food products has been carried out using electronic senses such as electronic nose (e-nose) and electronic tongue (e-tongue), the sensory profiles of strawberries and blueberries as analyzed by these instruments and their correlation to corresponding descriptive analysis of these berries have been the subject of a very few studies. The aim of this study was to characterize flavor profiles of strawberries and blueberries over a period of 5 days stored at 4°C using a descriptive sensory panel and electronic senses and correlate with the sensory panel data. The sensory panel's ratings followed a downward shift in different descriptive aroma, taste, and flavor attributes during the storage. Acceptable Discrimination Index (DI) was observed both in e-nose (DI ≥ 82) and e-tongue (DI ≥ 90) except for one commercial blueberry which had negative DI in e-tongue which means that these instruments exhibited satisfactory performance to discriminate the berries. The majority of the volatile compounds in the strawberry and blueberry consisted of esters, aldehydes, ketones, and furans – totaling 107 and 145 volatile compounds, respectively, through e-nose detection. Furaneol (4-Hydroxy-2,5-dimethyl-3-furanone) which imparts a distinct ripe aroma in strawberries increased (0.71±0.01–5.92±0.01 mg/mL) in all commercial strawberries throughout these 5 days with significant ($P < 0.01$) positive correlation to overripe aroma attribute ($r = 0.806$) but was negatively correlated to floral ($r = -0.651$), green ($r = -0.864$), and pungent ($r = -0.704$) aroma attributes analyzed by a descriptive panel. An aroma profile of a blueberry cultivar named Titan, which was locally grown at ambient (AT) and elevated temperatures (ET) was analyzed using a descriptive panel and e-nose. The ET growing condition resulted in significantly less ($P < 0.05$) sourness than

AT (2.63±0.04 and 4.78±0.05 on a 15-cm line scale, respectively) as per descriptive analysis and no carboxylic acid formation with a higher presence of sulfurous compounds usually associated with undesirable aroma notes as detected by the e-nose. The descriptive analysis data was well-correlated with the e-nose ($R^2 \geq 0.9095$) and e-tongue ($R^2 \geq 0.9114$) measurements by PLSR (Partial Least Square Regression), which indicates their superior potential and excellent capability to predict the aroma and taste qualities of strawberries and blueberries based on corresponding instrumental analyses.

1. Introduction

Strawberry (*Fragaria x ananassa*) and blueberry (*Vaccinium* spp.) are one of the most highly consumed fruits all over the world because of its superior sensory qualities and high nutritional values. The worldwide popularity of these fruits is mainly due to their eye-appeasing color, delightful taste, juicy fibrous mouthfeel, and exquisite flavor (Sotelo-González et al., 2023; Zhao et al., 2020). Furthermore, its high nutritional values have made it a top choice among health-conscious people who try to obtain potential health benefits from their daily diet. The presence of essential vitamins, minerals, and dietary fiber along with antioxidants such as flavonoids, polyphenols, vitamin C, and other bioactive compounds constitutes the rich nutrient profile of strawberry and blueberry - thus - effectively making them as functional superfoods (Kalt et al., 2019; Palumbo et al., 2022). In fact, strawberry and blueberry are two of the most consumed fruits among all types of berries in the USA (Kramer et al., 2021) as well as throughout the earth because of their distinctive aroma and highly likable flavor (Yan et al., 2018). For these reasons, strawberries and blueberries are considered to be the major berry crops not only in the USA but also around the entire globe due to their economic importance and high consumer demand (Lewers et al., 2020; Sater et al., 2020). In the US (United States), the utilized production of strawberry and cultivated blueberry were estimated to be 1.33 million tons and 330,070 tons of fresh equivalent, respectively, (USDA-NASS, 2022a). Moreover, the value of utilized production of strawberry and cultivated blueberry for 2021 US economic year was reported to be $3.42 billion USD (US dollars) and $1.02 billion USD, respectively, making them the second and fourth mostly-valued non-citrus fruits in the US in 2021 (USDA-NASS, 2022b).

The consumer acceptability of strawberry and blueberry is dependent on a fusion of complex attributes influencing the sensory quality of these fruits. While making the initial purchase decision at first, consumers usually make up their mind based on the fruits' appearance by evaluating their color intensity, texture glossiness, and fruit size (He et al., 2021; Lewers et al., 2020). Secondly, the fruit aroma has a profound effect on the consumers' buying intent and highly correlated to the consumers' overall liking of these fruits. To be specific, consumers generally take note of the fruits' appearance for their first impression and then taking into account the aroma pleasantness for the initial assessment of fruit quality (Dias et al., 2023; Ikegaya et al., 2019). It is afterward that the likability of the taste, flavor, and mouthfeel of the fruits is taken into consideration on whether to make the return purchase or not. In short, the aroma, taste, and flavor along with texture and appearance of strawberries and blueberries are the main sensory attributes that influence consumer acceptance and preference and are directly linked to the economic profit as well as the financial success of strawberry and blueberry growers who cultivate and produce it commercially (Gunness et al., 2009; Mennella et al., 2017).

Sensory attributes of strawberries and blueberries have been investigated by numerous studies (Plotto et al., 2013; Gilbert et al., 2015; Palumbo et al., 2022; Yan et al., 2020;) Plotto et al. (2013) focused on the importance of sensory evaluation for breeding new strawberry cultivars with improved flavor profiles for consistently higher strawberry flavor and sweetness coupled with superior agronomic traits (Plotto et al., 2013). However, it takes time and money to conduct sensory evaluation using human panels, making it difficult to be used in the breeding program. To save time and money, researchers have used instruments such as electronic senses (electronic nose and tongue) and gas chromatography (GC) to correlate with human panel data to understand future potential for sensory panel replacement. For example, the volatile aroma compounds detected at half-red and red maturity stages of strawberries were well-correlated to the selectivity and sensitivity of e-nose responses indicating its potential to discriminate strawberry ripeness

(Palumbo et al., 2022). The descriptive sensory analysis of different strawberry cultivars when correlated to their corresponding volatile analysis by GC-FID (Gas Chromatography – Flame Ionization Detector) revealed specific volatiles such as γ-dodecalactone and 6-methyl-5-hepten-2-one to increase consumer likability, thus, to be considered for targeted breeding (Fan et al., 2021a). The flavor, sweetness, and texture of blueberries positively influenced ($R^2 = 0.63–0.70$ at $P < 0.001$) overall consumer liking of southern highbush varieties with sourness negatively affecting sensory acceptance ($R^2 = 0.55$), whereas the breeding targets for better tasting blueberries with improved consumer affinity were pointed towards increasing fructose, 2-heptanone, and β-caryophyllene oxide while maintaining pH within 3.2–3.5 range (Gilbert et al., 2015). In blueberries, the overall main groups of volatile compounds have been reported to be esters (e.g., ethyl acetate, ethyl-2-methylbutanoate, ethyl propanoate, methyl isovalerate), aldehydes (e.g., hexanal, E-2-hexanal), terpenoids (e.g., linalool, geraniol, eucalyptol, α-terpeniol, eugenol), leaf alcohol (e.g., (Z)-3-hexen-1-ol) and ketone (e.g., 1-octen-3-one) (Yan et al., 2020; Forney et al., 2022).

Although many studies have explored different ways to correlate e-nose or GC (Gas Chromatography) with human panel data, little research has been done to correlate both e-nose and e-tongue with descriptive panels. Therefore, the main objective of this study was to characterize the flavor profiles of strawberries and blueberries by sensory and instrumental analyses (electronic senses) over a period of 5 days stored at 4°C and then to find relationships between them.

2. Materials and Methods

2.1. Ethics Statement

The prospect of sensory evaluation of strawberries and blueberries using human subjects (i.e., descriptive panel) was approved by the Institutional Review Board (IRB) of Auburn University with Exempt Protocol # 22-039 EX 2202. Everyone who performed as a trained panelist participated voluntarily by signing an informed consent form before they were allowed to be a part of this research.

2.2. Materials

All the food materials utilized in this investigation namely sucrose, turbinado sugar, citric acid, white vinegar, alum, honey, wasabi paste, blackberry flavor, spring water, unsalted crackers, and geraniol were non-GMO, food grade and collected from the Walmart and Kroger grocery stores located in Auburn, Alabama. Vanillin was bought from Fisher Scientific (Belgium), whereas caffein, Methyl isoborneol, (Z)-3-hexenal, and Furaneol were purchased from Sigma-Aldrich (USA). All the product details of these materials are mentioned in Table 3.1.

Table 3.1. Materials used in this study with detailed product information.

Materials	Product Details
Sucrose	Smidge and Spoon Granulated Sugar (Distribute by The Kroger Co., Cincinnati, OH)
Turbinado sugar	Sugar In The Raw® Granulated (Cumberland Packing Corp.)
Citric acid	Milliard™ Citric Acid (Milliard Brands, Lakewood, NJ)
White Vinegar	Heinz Distilled White Vinegar (5% Acidity) (Kraft Heinz Foods, Pittsburg, PA)
Alum	Great Value™ Alum (Walmart Inc., Bentonville, AR)
Honey	Great Value™ 100% Honey (Walmart Inc., Bentonville, AR)
Wasabi paste	S&B Wasabi Prepared Wasabi in Tube (Tokyo, Japan)
Blackberry flavor	Lorann Oils Blackberry Flavor (Lorann Oils, Inc., Lansing, MI)
Spring water	100% Natural DeerPark® Spring Water (Chesapeake, VA)
Unsalted crackers	Great Value™ Unsalted Tops Saltine Crackers (Walmart Inc., Bentonville, AR)
Geraniol	Geranium Essential Oil, 100% Pure & Natural, Therapeutic Grade (Majestic Pure Cosmeceuticals, San Diego, CA)
Vanillin	Fisher Chemical Vanillin Crystalline (Fisher Scientific, Geel, Belgium)
Caffeine	Caffein anhydrous, 99%, FCC, FG (Sigma-Aldrich Co., St. Louis, MO)
Methyl isoborneol	2-Methylisoborneol; ≥98.0%, GC (Sigma-Aldrich Co., St. Louis, MO)
(Z)-3-hexenal	Cis-3-Hexanal Solution, 50% in triacetin, Stabilized (Sigma-Aldrich Co., St. Louis, MO)
Furaneol	4-Hydroxy-2,5-dimethyl-3(2H)-furanone; ≥ 98%, FCC, FG (Sigma-Aldrich Co., St. Louis, MO)

Table 3.2. Description of commercially grown strawberry and blueberry samples used for sensory evaluation.

Fruit Type	Brand Names	Company Information	Recoded Sample Names	Product Information
Strawberry	Foxy®	BlazerWilkinsonGee, LLC., Salinas, CA 93908 U.S.A	SB1	California Strawberries; Product of USA
	California Giant Berry Farms®	California Giant, Inc., Main Office: Watsonville, CA 95077, USA	SB2	Product of USA
	Driscoll's Only the Finest Berries™	Driscoll's Inc., Watsonville, CA 95027, USA	SB3	Certified USDA Organic; Product of USA
Blueberry	Regenerate®	Distributed by Southern Press & Packing, 1865 Peacock Dairy Road Blackshear, GA 31516, USA	BB1	Georgia Grown; Product of USA
	California Giant Berry Farms®	California Giant, Inc., Main Office: Watsonville, CA 95077, USA	BB2	U.S. No. 1 Grade, Georgia Grown; Product of USA
	Simple Truth Organic™	Distributed by The Kroger Co., Cincinnati, Ohio 45202, USA	BB3	Certified Non-GMO USDA Organic; Organically grown – No preservatives; U.S. No. 1 Grade; Product of Mexico

2.3. Plant materials

At the first day (Day 1) of the sample evaluation, three commercial brands of strawberries and blueberries were purchased from Kroger and Publix (local supermarkets). Then the samples were transferred to the Poultry Science building of Auburn University and stored in a 4°C freezer for further analysis. The descriptions of commercial strawberry and blueberry samples used in this study are mentioned in Table 3.2 along with specific product information. Two blueberry cultivars named ‘Titan’ were grown locally by Dr. Courtney Leisner’s research group in the Biological Sciences department of Auburn University at ambient and elevated temperature conditions (the growth conditions are provided in Section 2.4). The fruits harvested from the ambient and elevated temperature treatments of these two cultivars were suffixed with AT and ET to denote the temperature conditions at which they were grown.

2.4. Growth Conditions of Locally-grown ‘Titan’ Blueberry Cultivar

2.4.1. Climate Data Sources

Weather data from Bacon County (Alma, GA, USA) was used determining future growing conditions for blueberry. This location was chosen because it is a representative area in the southeastern U.S. for blueberry production, corresponding to 49% of the total production area in Georgia and 28% in the southeast (USDA-NASS, 2022c). The Delta method (Anandhi et al., 2011) was used to obtain the projected daily minimum (T_{min}) and maximum (T_{max}) temperatures for the mid-century period (2041-2070). This was accomplished using three data sets: Reference, Multivariate Adaptive Constructed Analogs (MACA) Reference, and MACA Projected. The Reference data set consisted of daily near-surface T_{min} and T_{max} temperatures from 01 January 1981 to 31 December 2000 downloaded from the weather station (ID # GHCND:USW00013870) located at the Alma Bacon CO Airport (NOAA-NCEI, 2022).

MACA Reference and MACA Projected were obtained from the MACAv2-METDATA dataset (https://climate.northwestknowledge.net/MACA/index.php) that was generated by applying the MACA method (Abatzoglou & Brown, 2012), a statistical downscaling approach for bias correction, to the model output of 20 global climate models (GCMs) of the Coupled Model Inter-Comparison Project 5 (Hegewisch, 2015). For each GCM, the gridded 1/24-deg MACAv2-METDATA data sets for maximum and minimum temperatures for the location at latitude 31.5084 and longitude -82.4513 were obtained. MACA Reference consisted of monthly near-surface historical T_{min} and T_{max} from January 1981 to December 2000, while MACA Projected included data from the Representative Concentration Pathway (RCP) 8.5 scenario for the period 2041-2070. Data from the 20 GCMs was averaged, resulting in the final MACA Reference and MACA Projected data sets that contain the monthly mean T_{min} and T_{max} of all 20 GCMs. These averaged data sets were then used in the temperature projections.

2.4.2. Growth Chamber Experimental Design

The calculated temperature projections (i.e., hourly temperatures) for the reference (1981-2000) and mid-century (2041-2070) periods were used to design programs for a growth chamber experiment aimed at assessing the effects of ambient (i.e., historical) and elevated (i.e., projected) temperatures on blueberry. The set programs were operated in the ramping mode (a gradual and linear change in temperature between two set times). Temperature and photoperiod were changed every 14 days according to the method described by Leisner et al. (2018). Data for photoperiod were obtained from the NOAA Solar Calculator (NOAA-GML, 2022) using latitude 31.53580 and longitude -82.50670. Hourly temperatures and daily photoperiod were averaged in biweekly intervals starting on 01 October (Okie & Blackburn, 2011). Light intensity was also controlled to mimic sunrise and sunset through a four-step increase or decrease, respectively, over a 1-hour period. Incandescent lamps were kept on during the entire daylength. Temperature, relative humidity, and light intensity inside the growth chambers were recorded every 15 min using data loggers (Onset HOBO, Bourne, MA, USA).

Three-year old blueberry plants (Rabbiteye ecotype, cvs. Titan) were obtained from Bottoms Nursery (Concord, GA, USA) on 01 December 2021. Plants were received in 1-gallon pots filled with pine bark and peat moss mixture. Plants were kept outside (Paterson Greenhouse Complex, Auburn, AL, USA) until 01 February 2022 when the first signs of breaking of dormancy appeared. When majority of the plants had their floral buds at the bud swell stage, the plants were transferred into growth chambers (PGC-15, Percival Scientific, Perry, IA, USA) with controlled conditions as described earlier. A total of ten plants (2 cultivars x 5 replicates) were placed in each of the growth chambers assigned for ambient and elevated temperature treatments. The temperature treatments in the growth chambers lasted until the late bloom stage (i.e., 8.5 weeks), with temperature and photoperiod from early February to early April simulated. The plants were watered throughout the duration of the experiment to maintain adequate soil moisture. The growth chamber conditions of locally-grown Titan blueberries cultivated at ambient (AT) and elevated (ET) temperature conditions are given in Table 3.3 and Table 3.4, respectively.

Table 3.3. The growth chamber conditions of locally-grown Titan blueberries cultivated at ambient temperature (AT).

MM/DD	Daylength	Step 1 (6:00 AM)			Step 2 (6:20 AM)	Step 3 (6:40 AM)	Step 4 (7:00 AM)		Step 5 (2:00 PM)	Step 6 (Light 1 = 75%)		Step 7 (Light 1 = 55%)		Step 8 (Light 1 = 25%)		Step 9 (Light 1 = 0%)			Step 10		Step 11		Step 12	
		TEMP	Light 1	Light 2	Light 1	Light 1	TEMP	Light 1	TEMP	Time	TEMP	Time	TEMP	Time	TEMP	Time	TEMP	Light 2	Time	TEMP	Time	TEMP	Time	TEMP
1/7 - 1/20	10:17	5.2	25%	On	50%	75%	6.1	100%	16.0	3:17 PM	15.6	3:37 PM	15.6	3:57 PM	15.6	4:17 PM	14.6	Off	5:00 PM	13.3	10:00 PM	7.2	4:00 AM	4.7
1/21 - 2/3	10:34	5.9	25%	On	50%	75%	6.8	100%	17.1	3:34 PM	16.7	3:54 PM	16.7	4:14 PM	15.7	4:34 PM	15.7	Off	5:00 PM	14.4	12:00 AM	7.0	4:00 AM	5.4
2/4 - 2/17	10:56	6.7	25%	On	50%	75%	7.7	100%	18.1	3:56 PM	17.7	4:16 PM	16.8	4:36 PM	16.8	4:56 PM	16.8	Off	5:00 PM	15.4	2:00 AM	6.9	4:00 AM	6.2
2/18 - 3/3	11:22	8.9	25%	On	50%	75%	9.9	100%	20.1	4:22 PM	18.7	4:42 PM	18.7	5:02 PM	17.3	5:22 PM	17.3	Off	6:00 PM	15.8	4:00 AM	8.4	--	--
3/4 - 3/17	11:50	9.0	25%	On	50%	75%	10.1	100%	21.6	4:50 PM	20.1	5:10 PM	18.6	5:30 PM	18.6	5:50 PM	18.6	Off	6:00 PM	16.8	4:00 AM	8.5	--	--
3/18 - 3/31	12:17	11.3	25%	On	50%	75%	12.4	100%	23.4	5:17 PM	20.5	5:37 PM	20.5	5:57 PM	20.5	6:17 PM	18.8	Off	7:00 PM	17.1	4:00 AM	10.8	--	--
4/1 - 4/14	12:44	12.0	25%	On	50%	75%	13.0	100%	24.5	5:44 PM	21.5	6:04 PM	19.8	6:24 PM	19.8	6:44 PM	19.8	Off	7:00 PM	18.2	4:00 AM	11.4	--	--
4/15 - 4/28	13:09	13.9	25%	On	50%	75%	15.0	100%	26.9	6:09 PM	21.9	6:29 PM	21.9	6:49 PM	21.9	7:09 PM	20.1	Off	8:00 PM	18.6	4:00 AM	13.4	--	--
4/29 - 5/12	13:32	15.6	25%	On	50%	75%	16.7	100%	28.3	6:32 PM	23.5	6:52 PM	23.5	7:12 PM	21.8	7:32 PM	21.8	Off	8:00 PM	20.3	4:00 AM	15.0	--	--
5/13 - 5/26	13:52	18.0	25%	On	50%	75%	19.1	100%	30.3	6:52 PM	25.6	7:12 PM	24.0	7:32 PM	24.0	7:52 PM	24.0	Off	8:00 PM	22.6	4:00 AM	17.5	--	--
5/27 - 6/9	14:05	20.1	25%	On	50%	75%	21.1	100%	31.5	7:05 PM	25.6	7:25 PM	25.6	7:45 PM	25.6	8:05 PM	24.3	Off	9:00 PM	23.2	4:00 AM	19.6	--	--
6/10 - 6/23	14:11	21.2	25%	On	50%	75%	22.1	100%	32.3	7:11 PM	26.5	7:31 PM	26.5	7:51 PM	26.5	8:11 PM	25.2	Off	9:00 PM	24.2	4:00 AM	20.7	--	--
6/24 - 7/7	14:09	22.2	25%	On	50%	75%	23.2	100%	32.9	7:09 PM	27.4	7:29 PM	27.4	7:49 PM	27.4	8:09 PM	26.1	Off	9:00 PM	25.1	4:00 AM	21.8	--	--
7/8 - 7/21	14:00	22.9	25%	On	50%	75%	23.8	100%	33.9	7:00 PM	28.2	7:20 PM	28.2	7:40 PM	28.2	8:00 PM	26.9	Off	9:00 PM	25.9	4:00 AM	22.4	--	--
7/22 - 8/4	13:43	22.9	25%	On	50%	75%	23.8	100%	33.3	6:43 PM	29.3	7:03 PM	27.8	7:23 PM	27.8	7:43 PM	27.8	Off	8:00 PM	26.6	4:00 AM	22.4	--	--
8/5 - 8/18	13:23	22.5	25%	On	50%	75%	23.4	100%	32.9	6:23 PM	28.9	6:43 PM	28.9	7:03 PM	27.5	7:23 PM	27.5	Off	8:00 PM	26.3	4:00 AM	22.1	--	--
8/19 - 9/1	12:58	22.3	25%	On	50%	75%	23.2	100%	32.6	5:58 PM	30.1	6:18 PM	28.6	6:38 PM	28.6	6:58 PM	28.6	Off	7:00 PM	27.2	4:00 AM	21.9	--	--
9/2 - 9/15	12:33	21.1	25%	On	50%	75%	22.0	100%	31.1	5:33 PM	28.7	5:53 PM	28.7	6:13 PM	27.3	6:33 PM	27.3	Off	7:00 PM	25.9	4:00 AM	20.7	--	--
9/16 - 9/30	12:05	19.0	25%	On	50%	75%	19.9	100%	29.4	5:05 PM	26.8	5:25 PM	26.8	5:45 PM	26.8	6:05 PM	25.3	Off	7:00 PM	23.9	4:00 AM	18.6	--	--
10/1 - 10/14	11:37	16.6	25%	On	50%	75%	17.5	100%	27.2	4:37 PM	25.9	4:57 PM	25.9	5:17 PM	24.5	5:37 PM	24.5	Off	6:00 PM	23.0	4:00 AM	16.2	--	--
10/15 - 10/28	11:12	13.6	25%	On	50%	75%	14.7	100%	25.6	4:12 PM	24.1	4:32 PM	24.1	4:52 PM	24.1	5:12 PM	22.6	Off	6:00 PM	20.9	4:00 AM	13.1	--	--
10/29 - 11/11	10:48	12.0	25%	On	50%	75%	12.9	100%	23.2	3:48 PM	22.8	4:08 PM	21.8	4:28 PM	21.8	4:48 PM	21.8	Off	5:00 PM	20.3	4:00 AM	11.5	--	--
11/12 - 11/25	10:28	9.9	25%	On	50%	75%	10.9	100%	21.4	3:28 PM	21.0	3:48 PM	21.0	4:08 PM	20.0	4:28 PM	20.0	Off	5:00 PM	18.6	4:00 AM	9.4	--	--
11/26 - 12/9	10:13	8.5	25%	On	50%	75%	9.5	100%	20.0	3:13 PM	19.6	3:33 PM	19.6	3:53 PM	19.6	4:13 PM	18.6	Off	5:00 PM	17.1	4:00 AM	8.0	--	--
12/10 - 12/23	10:06	6.5	25%	On	50%	75%	7.5	100%	17.1	3:06 PM	16.7	3:26 PM	16.7	3:46 PM	16.7	4:06 PM	15.8	Off	5:00 PM	14.5	1:00 AM	7.2	4:00 AM	6.1
12/24 - 1/6	10:08	6.3	25%	On	50%	75%	7.2	100%	16.6	3:08 PM	16.3	3:28 PM	16.3	3:48 PM	16.3	4:08 PM	15.3	Off	5:00 PM	14.1	1:00 AM	6.9	4:00 AM	5.8

MM/DD = Month/ Date; TEMP = Temperature.

Table 3.4. The growth chamber conditions of locally-grown Titan blueberries cultivated at elevated temperature (ET).

MM/DD	Daylength	Step 1 (6:00 AM)			Step 2 (6:20 AM)	Step 3 (6:40 AM)	Step 4 (7:00 AM)		Step 5 (2:00 PM)	Step 6 (Light 1 = 75%)		Step 7 (Light 1 = 55%)		Step 8 (Light 1 = 25%)		Step 9 (Light 1 = 0%)			Step 10		Step 11		Step 12	
		TEMP	Light 1	Light 2	Light 1	Light 1	TEMP	Light 1	TEMP	Time	TEMP	Time	TEMP	Time	TEMP	Time	TEMP	Light 2	Time	TEMP	Time	TEMP	Time	TEMP
1/7 - 1/20	10:17	6.9	25%	On	50%	75%	7.8	100%	17.9	3:17 PM	17.5	3:37 PM	17.5	3:57 PM	17.5	4:17 PM	16.5	Off	5:00 PM	15.2	2:00 AM	7.1	4:00 AM	6.4
1/21 - 2/3	10:34	6.4	25%	On	50%	75%	8.6	100%	19.0	3:34 PM	18.6	3:54 PM	18.6	4:14 PM	17.6	4:34 PM	17.6	Off	5:00 PM	16.2	3:00 AM	6.4	4:00 AM	5.9
2/4 - 2/17	10:56	8.6	25%	On	50%	75%	9.6	100%	20.1	3:56 PM	19.7	4:16 PM	18.7	4:36 PM	18.7	4:56 PM	18.7	Off	5:00 PM	17.3	4:00 AM	8.1	--	--
2/18 - 3/3	11:22	10.8	25%	On	50%	75%	11.8	100%	22.1	4:22 PM	20.7	4:42 PM	20.7	5:02 PM	19.3	5:22 PM	19.3	Off	6:00 PM	17.8	4:00 AM	10.3	--	--
3/4 - 3/17	11:50	11.1	25%	On	50%	75%	12.2	100%	23.8	4:50 PM	22.2	5:10 PM	20.7	5:30 PM	20.7	5:50 PM	20.7	Off	6:00 PM	18.9	4:00 AM	10.6	--	--
3/18 - 3/31	12:17	13.4	25%	On	50%	75%	14.5	100%	25.6	5:17 PM	22.6	5:37 PM	22.6	5:57 PM	22.6	6:17 PM	20.9	Off	7:00 PM	19.3	4:00 AM	12.9	--	--
4/1 - 4/14	12:44	14.3	25%	On	50%	75%	15.4	100%	27.0	5:44 PM	24.0	6:04 PM	22.3	6:24 PM	22.3	6:44 PM	22.3	Off	7:00 PM	20.6	4:00 AM	13.8	--	--
4/15 - 4/28	13:09	16.3	25%	On	50%	75%	17.4	100%	29.4	6:09 PM	24.3	6:29 PM	24.3	6:49 PM	24.3	7:09 PM	22.5	Off	8:00 PM	21.0	4:00 AM	15.7	--	--
4/29 - 5/12	13:32	18.2	25%	On	50%	75%	19.3	100%	31.0	6:32 PM	26.2	6:52 PM	26.2	7:12 PM	24.4	7:32 PM	24.4	Off	8:00 PM	23.0	4:00 AM	17.6	--	--
5/13 - 5/26	13:52	20.7	25%	On	50%	75%	21.7	100%	33.1	6:52 PM	28.4	7:12 PM	26.7	7:32 PM	26.7	7:52 PM	26.7	Off	8:00 PM	25.3	4:00 AM	20.1	--	--
5/27 - 6/9	14:05	22.8	25%	On	50%	75%	23.8	100%	34.3	7:05 PM	28.4	7:25 PM	28.4	7:45 PM	28.4	8:05 PM	27.0	Off	9:00 PM	26.0	4:00 AM	22.3	--	--
6/10 - 6/23	14:11	23.9	25%	On	50%	75%	24.9	100%	35.1	7:11 PM	29.3	7:31 PM	29.3	7:51 PM	29.3	8:11 PM	28.0	Off	9:00 PM	27.0	4:00 AM	23.4	--	--
6/24 - 7/7	14:09	24.9	25%	On	50%	75%	25.9	100%	35.7	7:09 PM	30.1	7:29 PM	30.1	7:49 PM	30.1	8:09 PM	28.9	Off	9:00 PM	27.9	4:00 AM	24.5	--	--
7/8 - 7/21	14:00	25.6	25%	On	50%	75%	26.5	100%	36.8	7:00 PM	31.0	7:20 PM	31.0	7:40 PM	31.0	8:00 PM	29.7	Off	9:00 PM	28.6	4:00 AM	25.1	--	--
7/22 - 8/4	13:43	25.6	25%	On	50%	75%	26.5	100%	36.2	6:43 PM	32.1	7:03 PM	30.7	7:23 PM	30.7	7:43 PM	30.7	Off	8:00 PM	29.4	4:00 AM	25.2	--	--
8/5 - 8/18	13:23	25.4	25%	On	50%	75%	26.3	100%	35.8	6:23 PM	31.8	6:43 PM	31.8	7:03 PM	30.4	7:23 PM	30.4	Off	8:00 PM	29.2	4:00 AM	25.0	--	--
8/19 - 9/1	12:58	25.2	25%	On	50%	75%	26.1	100%	35.5	5:58 PM	33.0	6:18 PM	31.5	6:38 PM	31.5	6:58 PM	31.5	Off	7:00 PM	30.1	4:00 AM	24.8	--	--
9/2 - 9/15	12:33	24.0	25%	On	50%	75%	24.8	100%	33.9	5:33 PM	31.4	5:53 PM	31.4	6:13 PM	30.0	6:33 PM	30.0	Off	7:00 PM	28.7	4:00 AM	23.5	--	--
9/16 - 9/30	12:05	21.9	25%	On	50%	75%	22.8	100%	32.2	5:05 PM	29.6	5:25 PM	29.6	5:45 PM	29.6	6:05 PM	28.1	Off	7:00 PM	26.7	4:00 AM	21.4	--	--
10/1 - 10/14	11:37	19.3	25%	On	50%	75%	20.2	100%	29.9	4:37 PM	28.5	4:57 PM	28.5	5:17 PM	27.2	5:37 PM	27.2	Off	6:00 PM	25.7	4:00 AM	18.8	--	--
10/15 - 10/28	11:12	16.3	25%	On	50%	75%	17.3	100%	28.3	4:12 PM	26.8	4:32 PM	26.8	4:52 PM	26.8	5:12 PM	25.3	Off	6:00 PM	23.6	4:00 AM	15.8	--	--
10/29 - 11/11	10:48	14.4	25%	On	50%	75%	15.4	100%	25.7	3:48 PM	25.3	4:08 PM	24.3	4:28 PM	24.3	4:48 PM	24.3	Off	5:00 PM	22.9	4:00 AM	14.0	--	--
11/12 - 11/25	10:28	12.3	25%	On	50%	75%	13.3	100%	23.8	3:28 PM	23.4	3:48 PM	23.4	4:08 PM	22.4	4:28 PM	22.4	Off	5:00 PM	21.0	4:00 AM	11.8	--	--
11/26 - 12/9	10:13	10.6	25%	On	50%	75%	11.6	100%	22.3	3:13 PM	21.9	3:33 PM	21.9	3:53 PM	21.9	4:13 PM	20.8	Off	5:00 PM	19.4	4:00 AM	10.1	--	--
12/10 - 12/23	10:06	8.5	25%	On	50%	75%	9.5	100%	19.2	3:06 PM	18.9	3:26 PM	18.9	3:46 PM	18.9	4:06 PM	17.9	Off	5:00 PM	16.6	4:00 AM	6.9	--	--
12/24 - 1/6	10:08	8.1	25%	On	50%	75%	9.0	100%	18.7	3:08 PM	18.3	3:28 PM	18.3	3:48 PM	18.3	4:08 PM	17.4	Off	5:00 PM	16.1	4:00 AM	6.5	5:00 AM	6.3

MM/DD = Month/ Date; TEMP = Temperature.

2.5. Descriptive Analysis

A trained panel consisting of 16 expert panelists aged 22–34 years were trained heavily as per Spectrum™ Descriptive Analysis method for one hour every week throughout a month before they were asked to participate in the descriptive analysis of fruits. The panelists evaluated the all the commercially-purchased strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3) over a period of five consecutive days. Titan AT and Titan ET blueberries were evaluated only at the first day of sample evaluation (Day 1). On the first session, the panelists were presented with fresh strawberry and blueberry samples and asked to write down and describe all sensory attributes they could associate with the aroma, taste, and flavor of these fruits. Based on their responses from the first session, the panel leader discussed all the descriptive sensory attributes to calibrate the panel by generating a consensus in the group for the definition, reference standard, and intensity of each attribute as indicated in Table 3.5. Strawberry and blueberry samples masked with 3-digit random codes in 4 oz souffle cups were presented to the panelists at ~23°C in a tray with napkins and spring water along with unsalted crackers as palate cleansers. The trained panel (*n* = 16) evaluated the samples for different aroma (fruity, floral, sweet, green, pungent, overripe, overall aroma), taste (sweet, sour, bitter), and flavor (fruity, floral, pungent, astringent, musty/earthy, malty, honey, green flavor, fermented/overripe, strawberry/blueberry flavor) intensities as listed in Table 3.5 on a 15-cm line scale (0 = lowest; 15 = highest).

Table 3.5. Descriptive sensory attributes of strawberry and blueberry along with their definitions, reference standards, and perceived intensities on a 15-cm line scale.

Attributes	Definition	Reference Standard	Scale Intensity
Aroma attributes			
Fruity	A blend of sweet and floral aroma notes perceived in ripe fruits	One drop of blackberry flavor on a cotton ball	11
Floral	Somewhat sweet aromatics typical of flowers and fruits	One drop of geraniol in 1 L distilled water	8
Sweet	Sweet aroma perceived in fruit or flowers	0.5 g of vanillin in 500 mL distilled water	5.5
Green	Slightly pungent, sharp aroma perceived in parsley	25 g of fresh parsley rinsed, chopped, and added to 300 mL water; liquid part filtered after 15 minutes	9
Pungent	Sharp sensation that physically penetrates through nasal cavity	1 g of wasabi paste in 50 mL water	10
Overripe	Aroma emitted from overly mature fruits prone to decay	Overnight storage of overripe strawberry/ blueberry stored at 25°C	10
Overall aroma	Aroma emitted from fresh ripe strawberry/ blueberry	Strawberry/ blueberry fruit puree	10
Taste attributes			
Sweet	Basic sensation of tasting sucrose	2.0% sucrose solution	2
		5.0% sucrose solution	5
Sour	Basic sensation of tasting acetic acid *	0.05% citric acid solution	2
		0.08% citric acid solution	5
Bitter	Basic sensation of tasting caffein	0.05% caffeine solution	2
		0.08% caffeine solution	5
Flavor attributes			
Fruity	A blend of sweet and floral aroma notes perceived in ripe fruits	One drop of blackberry flavor on a cotton ball	11
Floral	Somewhat sweet aromatics typical of flowers and fruits	One drop of geraniol in 1 L distilled water	8
Pungent	Sharp sensation that physically penetrates through nasal cavity	One part vinegar mixed with 8 parts water	8
Astringent	Shrivels felt in tongue while tasting tannins or alum solution	0.125% alum solution	7
Musty/ earthy	Somewhat sweet, heavy aroma emitted from moist dark earth or decomposing foliage	One drop of 50 ppb methyl isoborneol in a cotton ball; served in a 2 oz cup	5
Malty	Flavor perceived as earthy or roasted	50 g/L turbinado sugar solution	10
Honey	Flavor perceived to have subtle floral notes	75 g/L honey solution	11
Green flavor	Slightly pungent, sharp aroma perceived in parsley	One drop of 1.5 ppm (Z)-3-hexenal in a cotton ball; served in a 2 oz cup	9
Fermented/ overripe	Off-flavor perceived while chewing	Overnight storage of overripe strawberry/ blueberry stored at 25°C	10
Strawberry/ blueberry flavor	Flavor of fresh ripe strawberry/ blueberry	Strawberry/ blueberry fruit puree	12

* Jung et al. (2017)

2.6. E-Nose Analysis

The volatile profiles of the strawberry and blueberry samples were measured with Heracles Neo e-nose (Alpha MOS, Toulouse, France). At first, all the strawberry and blueberry samples were pureed using a 16 oz Ninja® NJ110GR Food Chopper (Needham, MA) having 200W power pod. 2 g puree of each sample was then transferred immediately to 22.5×75 mm e-nose headspace vials and sealed airtight with aluminum caps containing PTFE/silicone septum. Afterwards, the vials were incubated at 50°C with 500 ppm continuous stirring for 20 minutes inside the e-nose incubation chamber to generate volatiles on the vials' headspace. Then, the e-nose auto-sampler, which is also dubbed as the robotic arm, transferred 5000 μL of headspace volatiles from the vials into the trap at 125 μL/s with the initial trap condition set at 40°C for 50 seconds on 1 mL/min constant flow and 10 mL/ min split mode until 240°C trap desorption temperature. For the chromatographic analysis, H_2 was used as the carrier gas at 1 mL/min flow rate to separate the volatiles inside the non-polar MXT-column (10 m × 180 μm) with FIDs (i.e., flame ionization detectors). The compound identification was carried out according to their Kovats retention indices using AroChemBase (Version 2021-7.2.8, AlphaMOS). All the peaks of respective compounds were analyzed in triplicates (n = 3) and their corresponding peak areas were reported as mean ± SE (i.e., Standard Error).

2.7. E-tongue Analysis

The taste profiles of commercial strawberry and blueberry samples' non-volatile compounds were analyzed using α-Astree e-tongue (Alpha MOS, Toulouse, France). At first, the strawberries and blueberries were juiced using a Breville® BJE430SIL Electric Juicer to dilute 5 mL of juice into 15 mL of distilled water to prepare 20 mL liquid sample in e-tongue beakers for the taste analysis. The e-tongue system was equipped with #6 sensory array consisting of AHS, CTS, NMS, PKS, CPS, ANS, and SCS sensors. The AHS, CTS, and NMS sensors accounted for sourness, saltiness, and umami, respectively, whereas ANS, CPS, PKS, and SCS sensors operated in a cross-selective general-purpose approach to translate sensor potentials as PCA taste maps. The e-tongue analysis of each sample was repeated six times throughout 120 seconds of acquisition time for each sample to create a matrix of six data points. In between every sample analysis, the sensor array consisting of all six sensors was submerged into beakers of distilled water for 10 seconds of cleaning to prevent cross-contamination between samples. The first two and last data points were unselected to incorporate the remaining data points in the creation of PCA taste maps.

2.8. Strawberry Furaneol Quantification

The strawberry aroma acceptance has been reported to be positively influenced by a specific compound called furaneol (4-Hydroxy-2,5-dimethyl-3-furanone) (Pérez et al., 1996). To understand how the strawberry furaneol concentration is correlated to the trained panel ratings of the descriptive aroma attributes, the furaneol standard curve as shown in Figure 3.1 was built at 50°C within 0.50–64 mg/mL range using the same e-nose method described in the above-mentioned ‘e-nose analysis’ section.

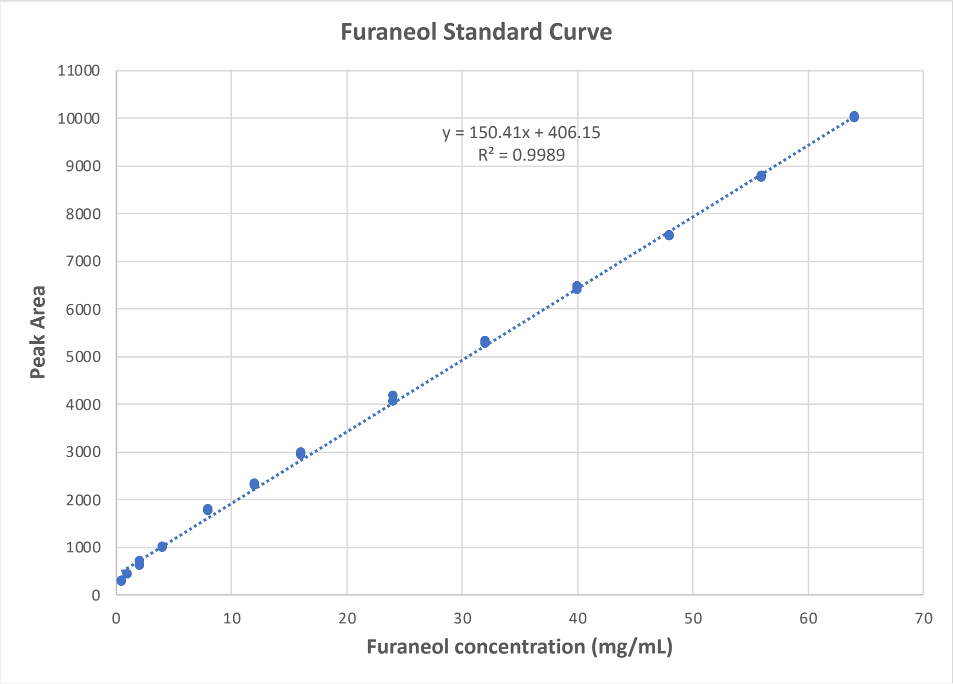


Figure 3.1. Standard curve to determine furaneol concentration (mg/mL) in strawberries.

It can be seen in Figure 3.1 that the furaneol standard curve had a R^2 value of 0.9989 which indicates that it was properly fit explaining 99.89% variations within the data. The regression equation obtained from this standard curve has been mentioned as Equation (1) and was subsequently used to quantify the furaneol content (mg/mL) of each strawberry sample based on their peak area calculated from the e-nose analysis.

$$y = 150.41\,x + 406.15 \text{ ----------------------- Equation (1)}$$

where, x = Furaneol concentration (mg/mL); y = Peak area calculated from e-nose analysis.

2.9. Statistical Analysis

Triplicates were maintained for all the experiments reported in this investigation and all results were mentioned as mean ± SE (Standard Error). For comparing the means with multiple comparisons, Tukey's HSD (Honestly Significant Difference) was conducted using XLStat

(Version 2023.1.6, AddinSoft, NY, USA) and differences with $P < 0.05$ were indicated as statistically significant. XLStat was also used to determine the correlation between the descriptive aroma attributes and furaneol content detected in the strawberries with Pearson's correlation. AlphaSoft (Version 2021-7.2.8, AlphaMOS, Toulouse, France) was used to generate the PCA (Principal Component Analysis) plots of strawberry and blueberry samples for their corresponding e-nose and e-tongue data as well as to correlate these instrumental data with descriptive analysis.

3. Results and Discussion

3.1. Descriptive Analysis

The descriptive analysis results of commercially-purchased strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3) rated for different aroma, taste, and flavor attributes on a 15-cm line scale are given in Table 3.6 and Table 3.7, respectively. Among all the descriptive aroma attributes, there was an increase in the fruity (5.25±0.05–7.97±0.03), sweet (3.78±0.43–4.88±0.03), overripe (3.25±0.05–5.84±0.05), and overall aroma (7.28±0.04–8.78±0.03) for the descriptive panels' ratings while the ratings on floral (3.06±0.03–4.88±0.06), green (2.09±0.04–4.44±0.04), and pungent (0.66±0.03–2.41±0.03) seemed to decrease over the 5 days' storage period in SB1, SB2, and SB3 strawberries (Table 3.6). As can be seen from Table 3.6, no significant difference (*P* < 0.05) was observed for all the aroma (floral, sweet, green, pungent, overripe, overall aroma), taste (sweet, sour, bitter), and flavor (pungent, astringent, musty/earthy, malty, honey, green, fermented/overripe, strawberry) attributes among the SB1, SB2, and SB3 strawberry samples. As shown in Table 3.7, similar trend was observed in BB1, BB2, and BB3 blueberries for the above-mentioned aroma attributes with an increase in fruity (5.25±0.05–7.97±0.03), sweet (3.78±0.43–4.88±0.03), overripe (3.25±0.05–5.84±0.05), and overall aroma (7.28±0.04–8.78±0.03) whereas a decrease in floral (3.06±0.03–4.88±0.06), green (2.09±0.04–4.44±0.04), and pungent (0.66±0.03–2.41±0.03) aroma attributes throughout the shelf-life. It is evident from Table 3.7 that the green aroma intensity of BB1 at Day 1 (4.44±0.04) was significantly higher (*P* < 0.05) than Day 5 (2.16±0.02) as evaluated by the trained panel, but no significant difference (*P* < 0.05) was observed among the storage days (Day 1 – Day 5) of all other aroma attributes for BB1, BB2, and BB3 blueberries (Table 3.7).

Table 3.6. Descriptive analysis of SB1, SB2, and SB3 strawberry samples throughout 5 days' storage period.

Attributes		SB1					SB2					SB3				
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5
Aroma	Fruity	7.38±0.03	7.41±0.05	7.91±0.06	8.03±0.04	8.19±0.03	6.03±0.06	6.31±0.03	7.31±0.05	7.47±0.05	7.47±0.05	6.23±0.02	6.47±0.04	7.16±0.03	7.34±0.05	7.69±0.04
	Floral	5.00±0.02	4.97±0.03	4.75±0.06	4.66±0.06	4.52±0.04	4.31±0.03	4.22±0.06	4.13±0.04	4.00±0.05	3.47±0.04	4.81±0.03	4.69±0.05	3.75±0.04	3.72±0.05	3.56±0.05
	Sweet	4.53±0.04	4.66±0.05	4.77±0.02	4.84±0.04	4.91±0.05	3.75±0.03	4.16±0.04	4.25±0.01	4.38±0.02	4.59±0.03	3.84±0.04	3.94±0.02	4.06±0.03	4.29±0.05	4.57±0.04
	Green	3.69±0.05	3.50±0.03	3.09±0.06	2.91±0.06	2.84±0.03	3.81±0.05	3.09±0.03	2.91±0.05	2.59±0.04	2.56±0.02	4.03±0.04	3.84±0.06	3.56±0.05	3.19±0.05	3.00±0.05
	Pungent	1.69±0.03	1.41±0.04	1.22±0.03	1.06±0.05	0.84±0.08	1.97±0.03	1.88±0.06	1.25±0.03	1.19±0.04	1.06±0.05	2.19±0.05	1.63±0.02	1.56±0.03	1.34±0.04	1.16±0.06
	Overripe	2.81±0.64	2.94±0.58	3.00±0.54	3.22±0.61	3.69±0.63	3.06±0.62	3.78±0.70	3.91±0.70	3.97±0.68	4.00±0.70	2.94±0.58	3.25±0.62	3.38±0.67	3.41±0.71	3.81±0.62
	Overall	8.56±0.40	8.91±0.44	9.00±0.49	9.38±0.47	9.38±0.50	8.19±0.56	8.28±0.37	8.53±0.44	8.63±0.40	8.91±0.48	7.78±0.60	8.06±0.44	8.19±0.56	8.50±0.42	8.81±0.51
Taste	Sweet	3.94±0.04	4.25±0.05	4.31±0.04	4.41±0.03	4.72±0.04	3.75±0.02	4.09±0.05	4.13±0.04	4.22±0.02	4.69±0.05	4.00±0.03	4.22±0.04	4.25±0.05	4.97±0.04A	5.44±0.05
	Sour	6.19±0.08	5.50±0.06	5.47±0.04	5.41±0.06	5.34±0.03	5.75±0.06	5.63±0.04	5.44±0.05	4.97±0.07	4.91±0.06	5.19±0.06	5.00±0.05	4.84±0.03	4.38±0.04	4.13±0.03
	Bitter	1.88±0.03	1.50±0.04	1.31±0.04	1.28±0.05	1.25±0.07	2.19±0.02	1.69±0.02	1.59±0.04	1.53±0.03	1.41±0.04	2.03±0.04	1.75±0.03	1.53±0.05	1.47±0.03	1.34±0.06
Flavor	Pungent	2.28±0.06	2.25±0.03	2.19±0.02	1.88±0.05	1.66±0.04	2.63±0.07	2.38±0.06	2.25±0.03	2.06±0.02	1.66±0.05	2.75±0.06	2.41±0.03	2.22±0.05	2.16±0.03	1.81±0.02
	Astringent	3.47±0.07	3.40±0.06	3.34±0.05	3.31±0.01	3.22±0.03	3.78±0.07	3.59±0.04	3.56±0.03	3.53±0.04	3.50±0.09	4.03±0.05	3.53±0.06	3.50±0.06	3.44±0.03	3.19±0.07
	Musty/ earthy	1.72±0.04	1.59±0.04	1.56±0.08	1.50±0.03	1.48±0.02	1.88±0.04	1.81±0.02	1.75±0.04	1.72±0.06	1.53±0.02	1.81±0.03	1.78±0.04	1.75±0.06	1.66±0.04	1.56±0.03
	Malty	3.03±0.05	2.88±0.06	2.84±0.06	2.41±0.04	2.34±0.05	3.06±0.04	2.66±0.02	2.50±0.05	2.38±0.05	2.34±0.04	3.47±0.06	3.34±0.05	2.53±0.02	2.50±0.05	2.47±0.04
	Honey	2.25±0.06	2.28±0.05	2.41±0.06	2.84±0.05	3.09±0.09	2.03±0.05	2.09±0.05	2.22±0.05	2.63±0.06	3.09±0.07	2.06±0.05	2.38±0.06	2.59±0.03	3.16±0.06	3.47±0.08
	Green	4.22±0.05	3.59±0.04	3.31±0.02	3.27±0.05	3.20±0.05	4.38±0.06	3.84±0.05	3.69±0.06	3.47±0.05	3.22±0.04	3.69±0.05	3.66±0.05	3.66±0.08	3.50±0.03	3.22±0.04
	Fermented/ overripe	2.59±0.03	2.63±0.06	2.66±0.07	2.94±0.04	3.41±0.02	2.63±0.05	2.78±0.06	3.19±0.02	3.53±0.06	3.79±0.04	2.72±0.06	2.97±0.04	3.09±0.03	3.19±0.05	3.81±0.04
	Strawberry	8.09±0.05	8.31±0.03	8.38±0.04	8.50±0.08	8.63±0.04	7.72±0.05	8.03±0.03	8.13±0.04	8.50±0.01	8.53±0.02	7.28±0.03	7.72±0.04	7.88±0.05	8.31±0.04	8.39±0.05

Table 3.7. Descriptive analysis of BB1, BB2, and BB3 blueberry samples throughout 5 days' storage period.

Attributes		BB1					BB2					BB3				
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5
Aroma	Fruity	6.25±0.05	6.53±0.04	6.94±0.03	7.31±0.05	7.59±0.06	6.41±0.04	6.66±0.06	6.78±0.05	7.25±0.04	7.97±0.03	5.25±0.05	5.88±0.06	6.03±0.05	6.66±0.04	6.78±0.05
	Floral	4.75±0.05	4.16±0.06	3.66±0.03	3.63±0.04	3.44±0.03	4.88±0.06	4.50±0.03	4.38±0.05	3.81±0.04	3.47±0.03	4.19±0.04	4.25±0.06	3.31±0.04	3.23±0.02	3.06±0.03
	Sweet	3.88±0.51	4.22±0.46	4.38±0.59	4.84±0.53	4.88±0.03	4.00±0.43	4.06±0.46	4.31±0.61	4.44±0.46	4.59±0.41	3.78±0.43	3.91±0.51	4.06±0.46	4.38±0.51	4.41±0.40
	Green	4.44±0.04^{A}	2.91±0.06^{AB}	2.88±0.05^{AB}	2.47±0.04^{AB}	2.16±0.02^{B}	4.03±0.05	2.69±0.04	2.56±0.04	2.43±0.02	2.09±0.04	4.06±0.04	2.56±0.05	2.47±0.06	2.34±0.03	2.21±0.04
	Pungent	1.78±0.05	1.69±0.04	1.31±0.04	1.25±0.02	0.97±0.03	1.63±0.05	1.56±0.04	1.34±0.03	1.22±0.02	0.66±0.03	2.41±0.03	1.75±0.06	1.66±0.05	1.41±0.04	1.16±0.03
	Overripe	3.97±0.03	4.25±0.04	4.34±0.03	4.44±0.05	4.47±0.08	3.25±0.05	3.40±0.06	3.44±0.03	3.63±0.05	4.19±0.06	4.22±0.04	5.32±0.03	5.41±0.02	5.50±0.07	5.84±0.05
	Overall	7.38±0.04	7.81±0.02	8.41±0.04	8.75±0.06	8.78±0.03	7.62±0.04	7.74±0.03	7.80±0.04	7.88±0.02	7.99±0.06	7.28±0.04	7.40±0.03	7.64±0.05	7.87±0.06	8.06±0.05
Taste	Sweet	5.81±0.03	6.09±0.06	6.16±0.05	6.28±0.04	6.84±0.06	5.63±0.05	6.04±0.06	6.43±0.05	6.55±0.04	6.72±0.06	4.00±0.03	4.16±0.04	4.25±0.06	4.81±0.06	5.00±0.07
	Sour	2.56±0.04	2.31±0.02	2.13±0.06	2.06±0.02	1.50±0.07	2.97±0.03	2.88±0.05	2.56±0.06	2.44±0.05	2.00±0.04	5.41±0.05^{A}	4.44±0.02^{AB}	4.00±0.04^{AB}	3.16±0.06^{AB}	2.00±0.05^{B}
	Bitter	1.50±0.04	1.36±0.03	1.16±0.02	1.09±0.03	0.78±0.02	1.34±0.04	1.22±0.02	1.10±0.03	1.02±0.02	0.88±0.03	2.34±0.04	2.24±0.05	2.22±0.02	2.16±0.04	1.69±0.03
Flavor	Pungent	1.88±0.05	1.71±0.04	1.50±0.04	1.41±0.03	1.28±0.04	1.97±0.02	1.63±0.04	1.59±0.02	1.46±0.03	1.22±0.04	3.13±0.03	2.81±0.05	2.53±0.03	2.16±0.02	1.84±0.03
	Astringent	3.34±0.06	2.84±0.05	2.76±0.04	2.69±0.03	2.61±0.02	3.44±0.05	3.26±0.03	3.13±0.06	2.97±0.05	2.66±0.04	4.31±0.02	4.25±0.03	3.81±0.04	3.53±0.05	3.50±0.06
	Musty/ earthy	2.41±0.05	1.87±0.02	1.72±0.04	1.41±0.03	1.16±0.02	2.00±0.04	1.94±0.03	1.72±0.04	1.69±0.02	1.59±0.03	2.69±0.03	2.47±0.04	2.38±0.02	2.31±0.03	2.00±0.04
	Malty	4.60±0.04	4.48±0.06	3.94±0.06	3.72±0.02	3.66±0.05	4.41±0.03	4.22±0.06	4.10±0.02	4.00±0.03	3.89±0.04	3.84±0.06	3.58±0.04	3.29±0.05	2.89±0.04	2.72±0.03
	Honey	3.19±0.06	3.53±0.04	3.88±0.05	4.41±0.02	4.75±0.03	3.66±0.03	3.88±0.04	3.94±0.02	3.97±0.03	4.09±0.04	2.42±0.04	2.59±0.04	2.78±0.02	2.94±0.03	3.06±0.02
	Green	2.94±0.04	2.63±0.05	2.38±0.04	2.29±0.02	2.13±0.03	3.44±0.04	2.98±0.05	2.87±0.06	2.56±0.04	2.09±0.05	4.03±0.02	3.00±0.03	2.88±0.02	2.47±0.03	2.38±0.04
	Fermented/ overripe	3.09±0.02	3.25±0.02	3.34±0.06	3.42±0.05	3.50±0.05	3.06±0.06	3.31±0.04	3.53±0.05	3.69±0.03	3.81±0.02	3.94±0.06	4.50±0.04	4.72±0.03	5.16±0.02	5.25±0.05
	Blueberry	7.97±0.04	8.12±0.03	8.25±0.04	8.34±0.05	8.53±0.03	8.09±0.04	8.15±0.05	8.22±0.03	8.28±0.04	8.31±0.05	6.88±0.03	7.06±0.04	7.26±0.04	7.68±0.03	7.88±0.05

Values denote mean ± standard error of each sensory descriptive attribute evaluated by a by a trained human panel (n = 16) on a 15-cm line scale.
^{A,B} indicate significant difference among sample means of the same row at $P < 0.05$.

The expert panel evaluation of commercial strawberries (SB1, SB2, SB3) for sweet, sour, and bitter taste revealed an increasing pattern in sweet taste with a decrease in sourness and bitterness throughout the shelf-life study (Table 3.6). The sweet taste (3.75±0.02−5.44±0.05) of commercially-purchased strawberries (SB1, SB2, SB3) increased over time but there was a decrease in the sourness (4.13±0.03−6.19±0.08) and bitterness (1.25±0.07−2.19±0.02) of the samples with a progression in 5 days of storage. No significant difference ($P < 0.05$) could be detected among the 5 days of storage for any of the strawberry taste attributes (Table 3.6). From the blueberry taste attributes data of Table 3.7, the descriptive analysis of store-purchased blueberries (BB1, BB2, BB3) for their taste attributes (sweet, sour, bitter) observed same tendency for those evaluated for SB1, SB2, and SB3 strawberries. Throughout the storage period, an increase in sweet taste (4.00±0.03−6.84±0.06) was reported with reduced ratings for sour (1.50±0.07−5.41±0.05) and bitter (0.78±0.02−2.34±0.04) tastes as time passed by for 5 days. Significantly higher ($P < 0.05$) sour taste was found in BB3 at Day 1 (5.41±0.05) as compared to Day 5 (2.00±0.05) although no significant difference ($P < 0.05$) could be detected among the storage days of BB1 and BB2. Also, the sweet and bitter taste attributes of all blueberry samples throughout these 5 days was not significantly different ($P < 0.05$). These data as given in Table 3.7 indicate relatively better taste profile of BB1 with comparatively higher sweetness and reduced sourness and bitterness than the other samples.

All the flavor attributes indicated in Table 3.6 and rated for SB1, SB1, and SB3 by the trained panelists ($n = 16$) increased for honey (2.03±0.05−3.47±0.08), fermented/overripe (2.59±0.03−3.81±0.04), and strawberry flavor (7.28±0.03−8.63±0.04) during 5 days' storage. In contrast, the expert panels' ratings for pungent (1.66±0.04−2.75±0.06), astringent

(3.19±0.07–4.03±0.05), musty/earthy (1.48±0.02−1.88±0.04), malty (2.34±0.04–3.47±0.06), and green (3.20±0.05–4.38±0.06) flavor attributes decreased over time. No significant difference ($P < 0.05$) was observed among the all the strawberry (SB1, SB2, and SB3) as well as the blueberry (BB1, BB2, BB3) samples for their 15-cm line scale ratings evaluated for any of the flavor attributes, indicating their similarity in flavor liking by the expert panel. The expert panels' liking scores for all the flavor attributes (pungent, astringent, musty/earthy, malty, honey, green, fermented/overripe, blueberry flavor) of the blueberries as listed in Table 3.7 (BB1, BB2, BB3) followed the same fashion as the commercial strawberries (SB1, SB2, SB3) during the storage period. An increase in honey (2.42±0.04–4.75±0.03), fermented/overripe (3.06±0.06−5.25±0.05), and blueberry flavor (6.88±0.03–8.53±0.03) was noted with a decrease in the pungent (1.22±0.04–3.13±0.03), astringent (2.61±0.02–4.31±0.02), musty/earthy (1.16±0.02−2.69±0.03), malty (2.72±0.03–4.60±0.04), and green (2.09±0.05−4.03±0.02) flavors throughout 5 days. All these data indicate preferable flavor profile of BB1 for its relatively higher blueberry flavor liking score (8.53±0.03) and lower ratings in pungent (1.28±0.04), musty/earthy (1.16±0.02), and green (8.53±0.03) flavor attributes.

To conclude, the berry flavor of the commercial strawberries and blueberries ranged from 7.28±0.03−8.63±0.04 and 6.88±0.03−8.53±0.03, respectively, throughout their storage at ~4°C for 5 days. In addition, these strawberries and blueberries had overall aroma liking within 7.78±0.60−9.38±0.50 and 7.28±0.04–8.06±0.05 range, respectively, during the shelf-life sensory evaluation. These findings may be interpreted as the store-bought strawberries and blueberries having acceptable flavor and overall aroma likability as evaluated by the descriptive panel throughout the entire duration of their investigated shelf-life. In other words, the flavor and overall aroma acceptance of commercial strawberries and blueberries may remain fairly satisfactory after they have been bought from the stores and kept in the refrigerator for 5 days.

Table 3.8 represents the descriptive analysis of local Titan AT and Titan ET blueberry cultivars grown at ambient and elevated temperature, respectively. No significant differences ($P < 0.05$) were observed among the aroma, taste and flavor attributes except sour taste. Sourness is one of the most important indicators of blueberry sensory quality along with sweetness and firmness (Sater et al., 2021). The taste evaluation of Titan AT and Titan ET by the descriptive panel revealed that Titan ET, which was grown in elevated temperature conditions, had significantly less ($P < 0.05$) sourness (2.63±0.04) than Titan AT (4.78±0.05). These results imply that higher temperature conditions in blueberries may result in less pronounced sourness.

Table 3.8. Descriptive analysis of Titan AT and Titan ET blueberry samples grown at ambient and elevated temperature conditions, respectively.

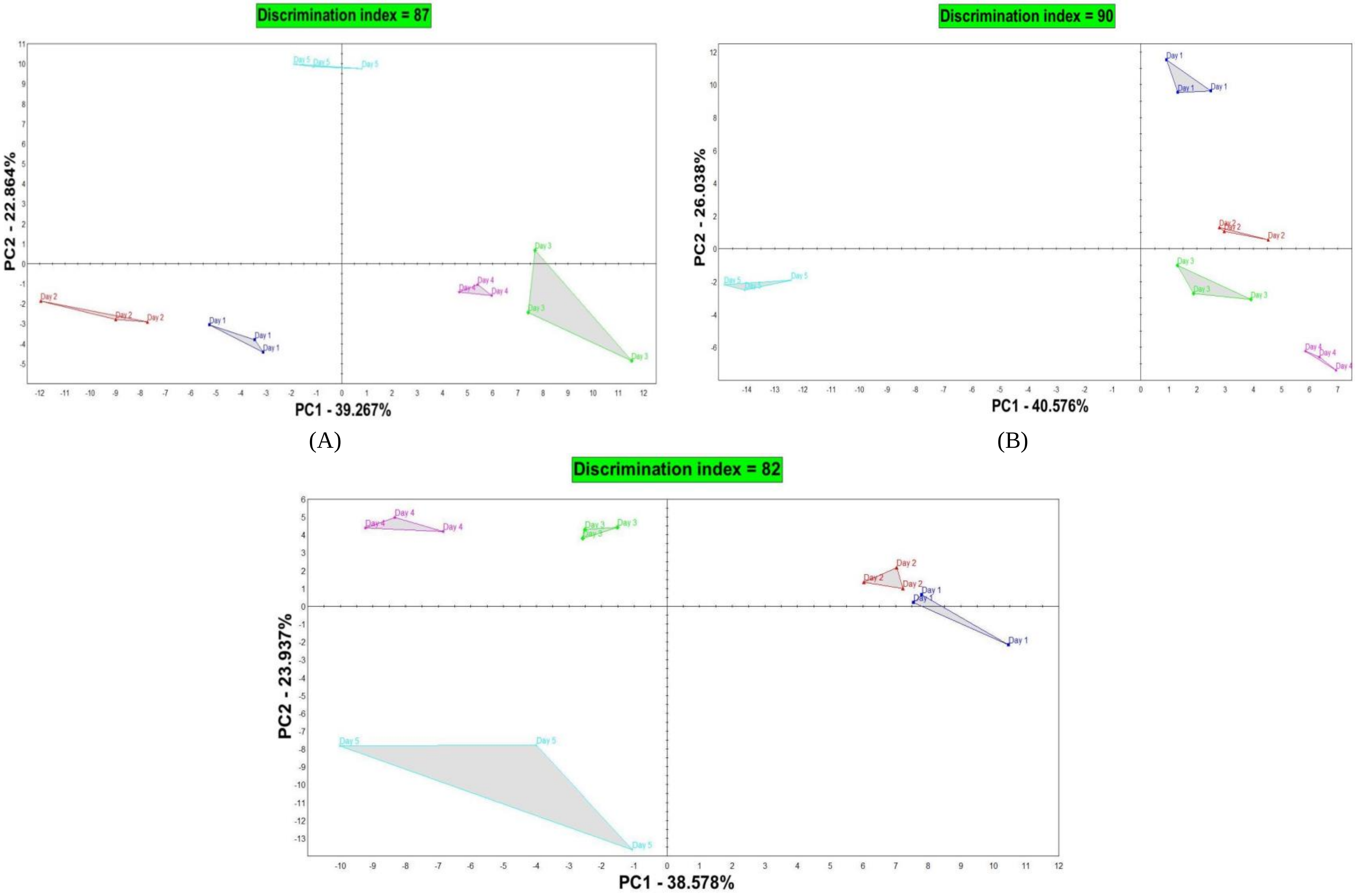
Attributes		Titan Blueberry Variety	
		Titan AT (Grown at ambient temperature)	Titan ET (Grown at elevated temperature)
Aroma	Fruity	5.41±0.05	5.22±0.02
	Floral	4.59±0.03	3.44±0.04
	Sweet	3.84±0.02	3.69±0.03
	Green	3.50±0.04	3.00±0.05
	Pungent	1.53±0.04	1.44±0.03
	Overripe	4.75±0.03	5.19±0.02
	Overall	7.31±0.06	7.72±0.05
Taste	Sweet	5.00±0.02	4.94±0.06
	Sour	4.78±0.05^{A}	2.63±0.04^{B}
	Bitter	1.91±0.02	1.69±0.04
Flavor	Pungent	2.94±0.06	2.16±0.04
	Astringent	4.97±0.03	3.59±0.05
	Musty/earthy	2.22±0.03	2.28±0.04
	Malty	3.31±0.05	3.84±0.06
	Honey	3.25±0.02	3.00±0.05
	Green	3.50±0.03	3.72±0.02
	Fermented/overripe	4.19±0.05	4.22±0.04
	Blueberry	7.94±0.02	7.16±0.06

Values denote mean ± standard error of each sensory descriptive attribute evaluated by a by a trained human panel (n = 16) on a 15-cm line scale.
^{A,B} indicate significant difference among sample means of the same row at $P < 0.05$.

3.2. E-nose Analysis

The changes in the volatile aroma profiles of SB1, SB2, and SB3 strawberry samples as detected by e-nose analysis during 5 days' storage have been shown as aroma maps via PCA plots in Figure 3.2. The PCA plot depicted in Figure 3.2A demonstrates the change in the volatile profiles of SB1 detected by the e-nose over 5 days that could explain 39.27% and 22.86% variations along the first two principal components PC1 and PC2, respectively, accounting for 62.13% explanation of total variability within the e-nose data with a Discrimination Index (DI) of 87. Figure 3.2B illustrates the volatile aroma change in SB2 as detected by the e-nose in the form of PCA plot which explained 66.61% total variability of the e-nose detection (PC1: 40.58%; PC2: 26.04%) with DI = 90. The volatile change in SB3 from Day 1 to Day 5 through e-nose detection is shown in Figure 3.1C in which total 62.52% variation within the e-nose data was explained by the PCA plot (DI = 82) with 38.58% and 23.94% variations explained across PC1 (first principal component) and PC2 (second principal component), respectively.

The e-nose detection for the change in overall volatile profiles of BB1, BB2, and BB3 blueberries throughout the shelf-life has been outlined in Figure 3.3 by means of PCA plots. The PCA plot in Figure 3.3A demonstrates the volatile change in BB1 with a 62.87% total explanation for the e-nose data variations by accounting for 38.02% and 24.85% variability along the first (PC1) and second (PC2) principal components, respectively, having a DI of 83. A total of 64.36% e-nose data variation for the volatile change in BB2 was described by the PCA plot depicted in Figure 3.3B with DI = 92 while the PC1 and PC2 was responsible for 39.52% and 24.84% explanation in data variability, respectively. Figure 3.3C illustrates the PCA plot of e-nose volatile analysis of BB3 with associated change in aroma intensities for 5 days that accounted for 66.634% total explanation of e-nose data variability having a DI of 95 and describing 41.449% variation through PC1 and 25.185% variability across PC2. The volatile aroma profile of locally cultivated Titan AT and Titan ET blueberries analyzed by the e-nose is demonstrated as the PCA plot in Figure 3.4. The variations of the e-nose data had a 70.744% total explanation by the PCA plot with a Discrimination Index of 91 (i.e., DI = 94) that accounted for 56.095% and 14.649% variations along PC1 and PC2 (i.e., first two principal components), respectively.

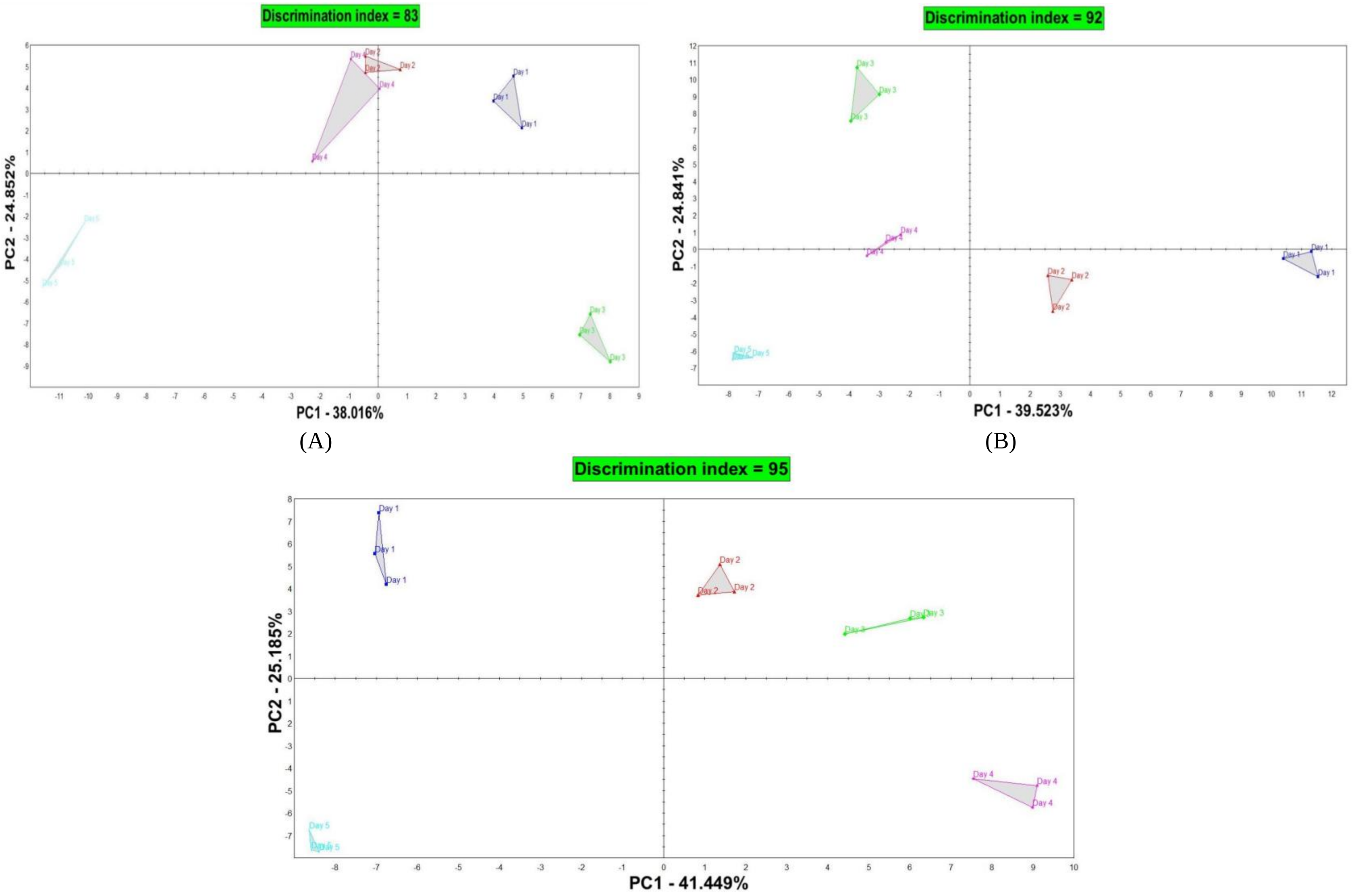


(A)

(B)

(C)

Figure 3.2. PCA plots showing the changes in the volatile aroma profiles of (A) SB1, (B) SB2, and (C) SB3 strawberries detected by the e-nose throughout 5 days' storage period.



(A)

(B)

(C)

Figure 3.3. PCA plots showing the changes in the volatile aroma profiles of (A) BB1, (B) BB2, and (C) BB3 blueberries detected by the e-nose throughout 5 days' storage period.

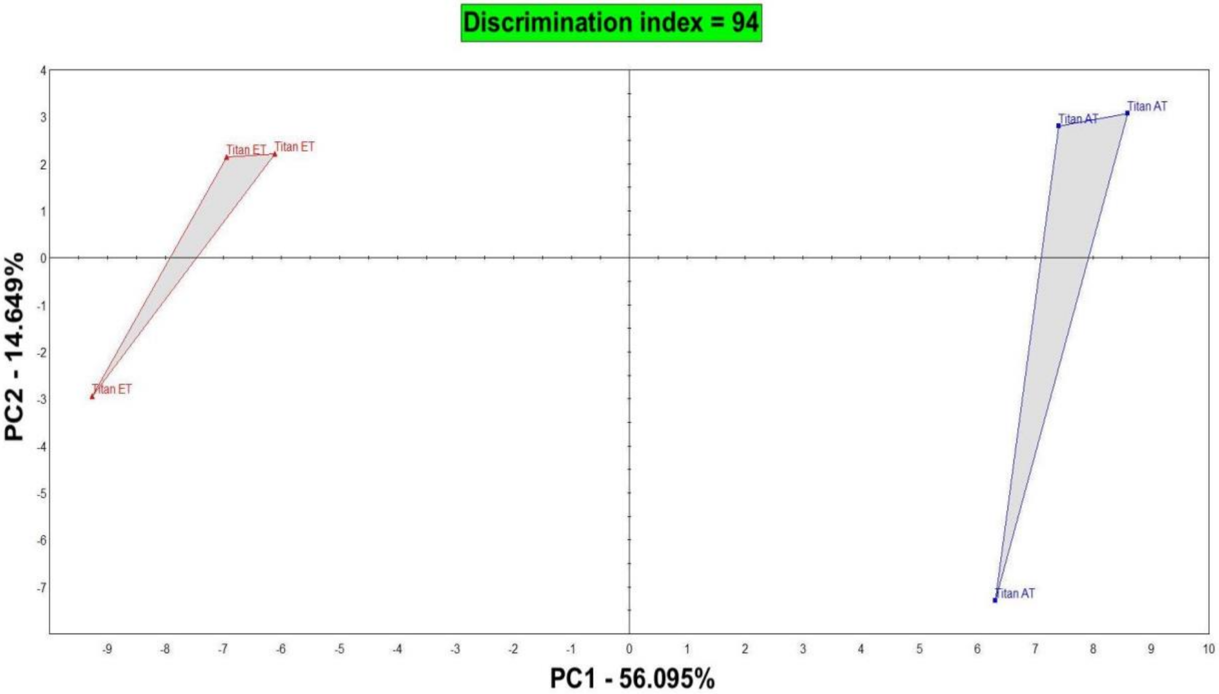


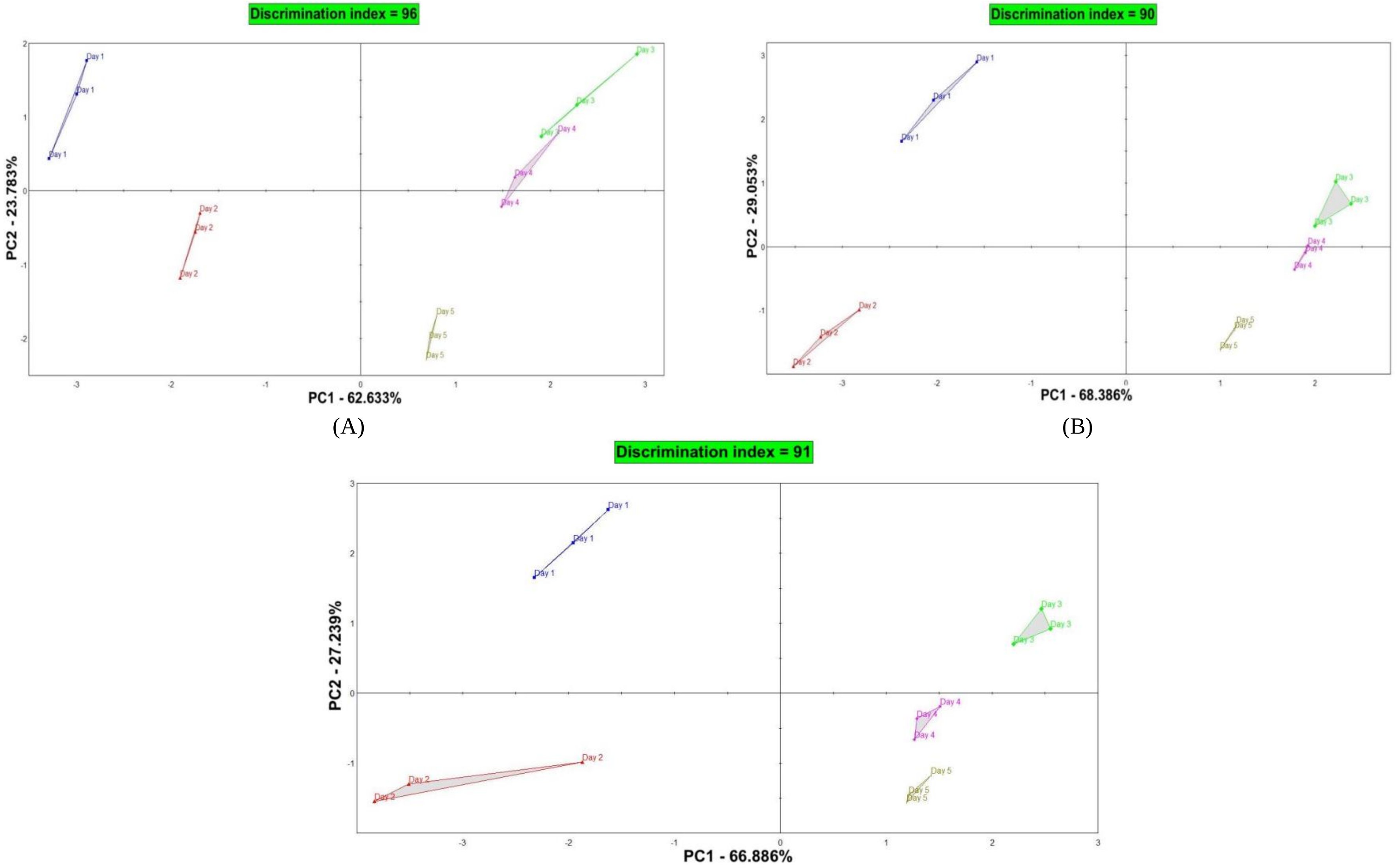
Figure 3.4. PCA plot showing the volatile aroma profiles of locally-cultivated Titan AT and Titan ET blueberries detected by the e-nose.

The correlation coefficients of PLSR (R^2) indicating the association between the e-nose data and the descriptive analysis for aroma attributes of commercial strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3) throughout five days are presented in Table 3.9. As shown in Table 3.9, the data from e-nose analysis were highly correlated to all the descriptive aroma attributes (fruity, floral, sweet, green, pungent, overripe, overall aroma) evaluated both for commercial strawberries ($R^2 \geq 0.9142$) and blueberries ($R^2 \geq 0.9095$) for all the 5 days of evaluation at $P < 0.05$ significance level. It means that all the PLS models could explain more than 91.42% variability within the fitted regression data, indicating high correlation between the e-nose analysis and trained panel liking scores for fruity, floral, sweet, green, pungent, overripe, and overall descriptive aroma attributes evaluate for the commercial strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3).

These findings suggest that e-nose has the potential to discriminate (DI ≥ 82) the volatile aroma profiles of strawberries and blueberries throughout a storage period of 5 days. These results also indicate that the difference in aroma volatiles of Titan blueberry cultivar grown in different temperature conditions can be detected using the e-nose. The overall delineation of total variations (≥ 62.13%) within the e-nose data as described by the PCA demonstrates the applicability of the e-nose to assess and distinguish the changes in volatile aroma profiles of strawberries and blueberries throughout their post-harvest storage. In this way, the e-nose was more sensitive than human sensory panel because its discrimination indices were very high (DI ≥ 83) even though the descriptive panel did not find any significant difference ($P < 0.05$) in any of the strawberry aroma attributes except ‘fruity’ and also for the ‘overall aroma’ of blueberries. Furthermore, high correlation ($R^2 \geq 0.9142$) between the e-nose data and descriptive analysis of all aroma attributes (fruity, floral, sweet, green, pungent, overripe, overall aroma) for all store-bought strawberry and blueberry samples (SB1, SB2, SB3, BB1, BB2, BB3) evaluated by the trained panel indicates that the e-nose may be potentially used to predict the descriptive panel liking scores for fruity, floral, sweet, green, pungent, overripe, and overall aroma throughout post-harvest storage based on the volatile aroma profile of strawberries and blueberries analyzed by this sensory instrument. These observations comply with the findings of Palumbo et al. (2022) who implemented PEN 3 e-nose (Airsense Inc., Germany) to distinguish ‘red’ or ‘half-red’ ripening stages of ‘Candonga’ strawberries performing PCA on their aroma volatile compounds. In addition, a novel e-nose comprising six semiconductor sensors of metal oxide could recognize strawberry freshness based on their aroma emission during post-harvest storage with 94.9% accuracy (Xing et al., 2018). The e-nose could characterize strawberry fruit maturity on five ripening stages ranging from white (unripe) to overripe and its sensor data could differentiate the fruits’ ripeness as per their volatile aroma profiles (Du et al.. 2010). Further, blueberries with repeated impacts were classified as per their difference in volatile aroma analyzed by an e-nose throughout 24 days’ post-harvest storage with 80–100% correct classification rates (Demir et al., 2011). All these available data indicate that the e-nose can be a valuable tool to detect the quality changes in strawberries and blueberries during post-harvest stages.

3.3. E-tongue Analysis

The PCA plots presented in Figure 3.5 are the taste maps of SB1, SB2, and SB3 strawberries indicating the changes in their non-volatile taste profiles during 5 days’ storage. Figure 3.5A demonstrates the taste change in SB1 through the PCA plot that described 86.42% total explanation in e-tongue data variability with high Discrimination Index (DI = 96) accounting for 62.63% and 23.78% variations across PC1 and PC2 (i.e., first two principal components), respectively. The e-tongue taste map of SB2 indicating the change in its non-volatile profile shown as the PCA plot in Figure 3.5B had a Discrimination Index (DI) of 90 which explained 97.44% explanation of total variability with PC1 and PC2 describing 68.39% and 29.05% of variations along their corresponding principal components, respectively. The PCA plot in Figure 3.5C illustrating the non-volatile change of SB3 during its 5-days storage had a DI = 91 and detailed 94.13% total explanation of variability within the e-tongue data having 66.89% and 27.24% variations described through PC1 and PC2, respectively. Figure 3.6 shows the non-volatile changes in BB1, BB2, and BB3 blueberries analyzed by e-tongue from the beginning to the last storage day (i.e., Day 1 to Day 5) as PCA plots. The taste change in BB1 as detected through e-tongue analysis is displayed in the PCA plot of Figure 3.6A which delineates 50.61% and 25.34% variations across PC1 and PC2, respectively, to describe 75.95% of whole variations in e-tongue measurements encompassing DI of 96. A total of 90.29% variability within e-tongue data with –0.1 Discrimination Index was explained by the PCA plot exhibited in Figure 3.6B to characterize the non-volatile change in BB2 having the first two principal components explained 59.78% (PC1) and 30.51% (PC2) variations. Figure 3.6C displays the e-tongue PCA plot indicating the change in non-volatile profile of BB3 with DI = 92 that accounts for 90.95% explanation of overall variations in the e-tongue analysis and 65.07% and 25.88% explanations of variability across the first two principal components PC1 and PC2, respectively.

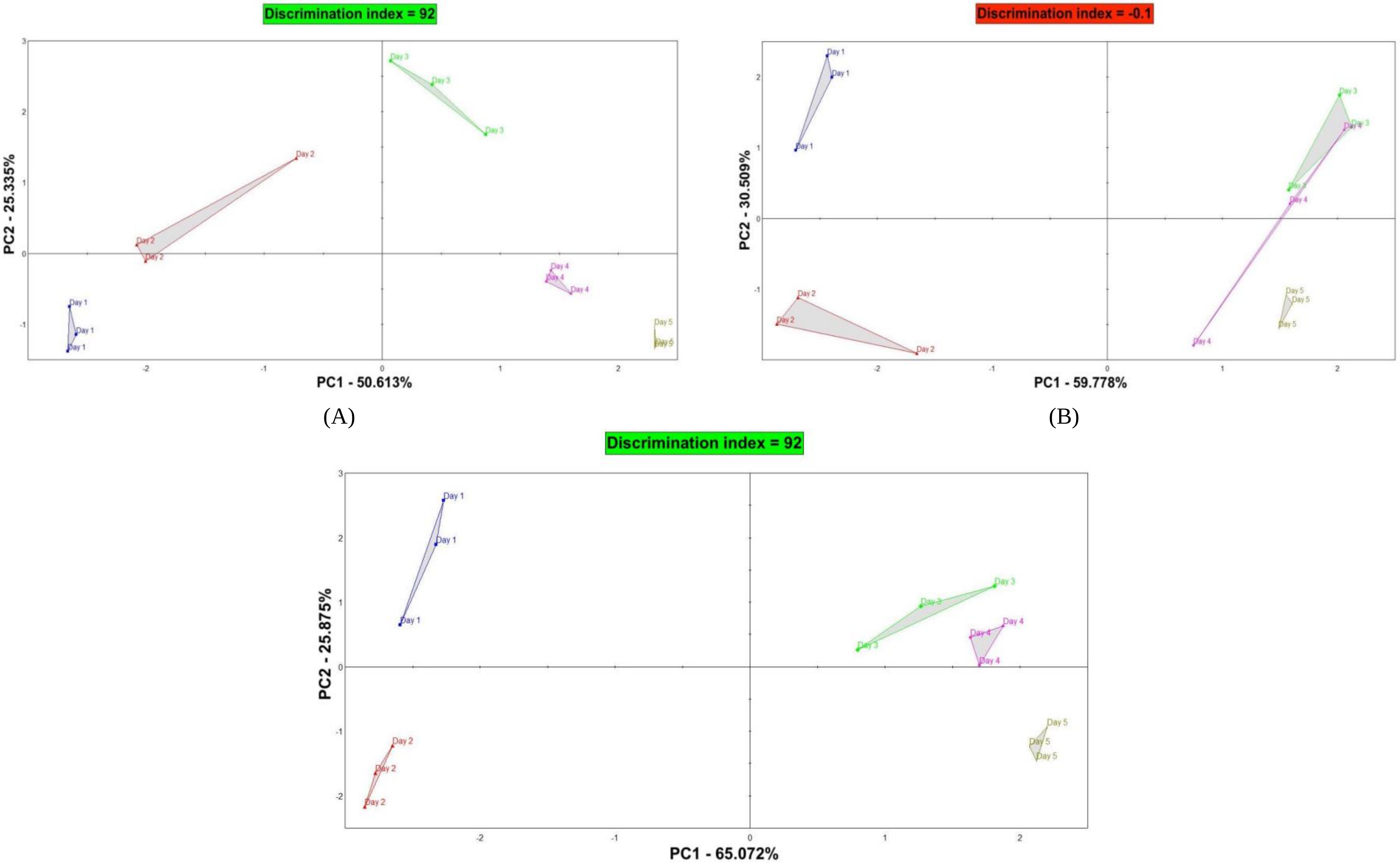


(A)

(B)

(C)

Figure 3.5. PCA plots showing the changes in the non-volatile taste profiles of (A) SB1, (B) SB2, and (C) SB3 strawberries detected by the e-tongue throughout 5 days' storage period.



(A)

(B)

(C)

Figure 3.6. PCA plots showing the changes in the non-volatile taste profiles of (A) BB1, (B) BB2, and (C) BB3 blueberries detected by the e-tongue throughout 5 days' storage period.

Table 3.9. PLSR correlation coefficients (R^2) indicating association between e-nose data and descriptive aroma attributes evaluated by trained human panelists ($n = 16$) over a period of 5 days.

Aroma attributes	R^2 for SB1, SB2, and SB3 Strawberries					R^2 for BB1, BB2, and BB3 Blueberries				
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5
Fruity	0.9881*	0.9690***	0.9771***	0.9740***	0.9209*	0.9938***	0.9528**	0.9927***	0.9887***	0.9708***
Floral	0.9846***	0.9822***	0.9733***	0.9614***	0.9142**	0.9929***	0.9628***	0.9960***	0.9265**	0.9738***
Sweet	0.9881*	0.9731***	0.9755***	0.9761***	0.9204**	0.9482**	0.9755***	0.9930***	0.9973***	0.9926***
Green	0.9801***	0.9722***	0.9889***	0.9921***	0.9821***	0.9240**	0.9541**	0.9936**	0.9840***	0.9707***
Pungent	0.9515**	0.9824***	0.9803***	0.9344***	0.9433**	0.9928***	0.9798*	0.9875***	0.9609***	0.9707***
Overripe	0.9663***	0.9822***	0.9764***	0.9571***	0.9600***	0.9095**	0.9876*	0.9960**	0.9942**	0.9722***
Overall	0.9651***	0.9712***	0.9727***	0.9774***	0.9303**	0.9161**	0.9935***	0.9936**	0.9976***	0.9873***

* means $P < 0.05$; ** means $P < 0.01$; *** means $P < 0.001$.

Table 3.10. PLSR correlation coefficients (R^2) indicating association between e-tongue measurements and descriptive taste attributes evaluated by trained human panelists ($n = 16$) over a period of 5 days.

Taste attributes	R^2 for SB1, SB2, and SB3 Strawberries					R^2 for BB1, BB2, and BB3 Blueberries				
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 1	Day 2	Day 3	Day 4	Day 5
Sweet	0.9386**	0.9792*	0.9934*	0.9564*	0.9585*	0.9923**	0.9537*	0.9270*	0.9834***	0.9965**
Sour	0.9275**	0.9722*	0.9952*	0.9629***	0.9725*	0.9928**	0.9283*	0.9114*	0.9733***	0.9924***
Bitter	0.9724*	0.9397**	0.9194*	0.9564*	0.9667***	0.9895**	0.9712*	0.9227*	0.9807***	0.9966**

* means $P < 0.05$; ** means $P < 0.01$; *** means $P < 0.001$.

The relationship between the e-tongue analysis and the descriptive taste attributes (sweet, sour, bitter) of commercial strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3) evaluated during the 5 days' shelf-life is mentioned in Table 3.10 in terms of the PLSR correlation coefficients (R^2). High correlation (significant at $P < 0.05$) was observed between the e-tongue data and descriptive panels' liking scores on sweet, sour, and bitter taste attributes with $R^2 \geq 0.9194$ evaluated for commercial SB1, SB2, and SB3 strawberries and $R^2 \geq 0.9114$ rated for BB1, BB2, and BB3 blueberries. These high R^2 values indicate that the e-tongue data has strong positive association with the descriptive analysis of commercial strawberries and blueberries judged for sweetness, sourness, and bitterness (descriptive taste attributes) by the expert panel on a 15-cm line scale. Further, more than 91.14% variations were explained by all of the PLS models ($R^2 \geq 0.9114$; the lowest R^2 being 0.9114) to correlate ($P < 0.05$) the e-tongue data to the descriptive taste attributes of commercial SB1, SB2, SB3 strawberries and BB1, BB2, BB3 blueberries.

All these data point towards the discrimination potential of the e-tongue to sense the non-volatile changes in strawberries and blueberries over five days with DI ≥ 90 except BB2 blueberry. The negative Discrimination Index (DI = – 0.1) of BB2 resulted from the overlapping of e-tongue triplicate triangles of Day 3 and Day 4 to imply similarity in the non-volatile taste profiles of BB2 blueberry during these days (Day 3 and 4). These high Discrimination Indices (DI ≥ 90) indicate that the e-tongue exhibited more sensitivity than the descriptive panel since the trained panelists could not distinguish no significant difference ($P < 0.05$) for sour and sweet tastes in store-bought strawberries (SB1, SB2, SB3) along with sweet and bitter tastes in locally grown Titan AT and Titan ET blueberries. Overall, the PCA revealed satisfactory explanation of total variability (≥ 75.95%) within the e-tongue data for its profiling of non-volatile changes inside strawberry and blueberry liquid matrix over time, thus, reasserting the previously-stated reasoning about e-tongue’s capacity to discriminate the taste profile of strawberry and blueberry throughout 5 days of storage. Moreover, strong association of the e-tongue analysis with all descriptive taste attributes (sweet, bitter, sour) of strawberries and blueberries points out the potential of this sensory device to estimate their predictive sweet, sour, and bitter taste scores for the changes in non-volatile constituents after harvest. These assessments are in line with the finding of Qiu et al. (2015) who successfully implemented α-Astree e-tongue (Alpha MOS) to classify and discriminate strawberry juices prepared using different processing methods. PLSR validation ($R^2 = 0.8304–0.8741$) achieved acceptable association between the e-tongue signals and physicochemical quality parameters such as pH, TSS/TA ratio, vitamin C etc. Gao et al. (2012) used e-tongue to distinguish different strawberry juices formulated with varying fruit ripeness. The PLSR correlation between e-tongue responses and several juice quality parameters lead to satisfactory prediction of pH, vitamin C, and soluble solids content with a prediction R^2 of 0.793. Zeng et al. (2020) used TS-SA402B e-tongue (Intelligent Sensor Inc.) to differentiate ‘Brightwell’ blueberry based on different growing altitudes and geographic origin inside China. Thus, the changes in non-volatile sensory characteristics of berries (i.e., strawberry and blueberry) can be evaluated using an e-tongue.

3.4. E-nose Detection of Volatile Aroma Profiles

In strawberries, a total of 107 number of volatile compounds were by the e-nose and their peak areas along with sensory descriptors are mentioned in Table 3.11. Thirty seven (37) of these volatile compounds have been previously reported by Cannon et al. (2015) in French ‘Ciflorette’ variety and 24 common volatile compounds were also identified by González-Domínguez et al. (2020) in strawberries grown in soilless system. In addition, 7 volatile compounds detected by Passa et al. (2023) in Western Greece strawberry cultivars matched with those reported in this study. The strawberry volatile profile classified in terms of volatile groups of all compounds is illustrated in Figure 3.7. Among all compounds, 25.23% of esters (27 compounds) were found in the highest amount followed by 14.95% of aldehydes with aromatic derivatives (16 compounds), 9.35% of ketones with aromatic derivatives (10 compounds), 8.41% of alcohols (9 compounds), 6.54% of terpenes and terpenoids (7 compounds), and 5.61% of furans (6 compounds) as per compounds identified in each group.

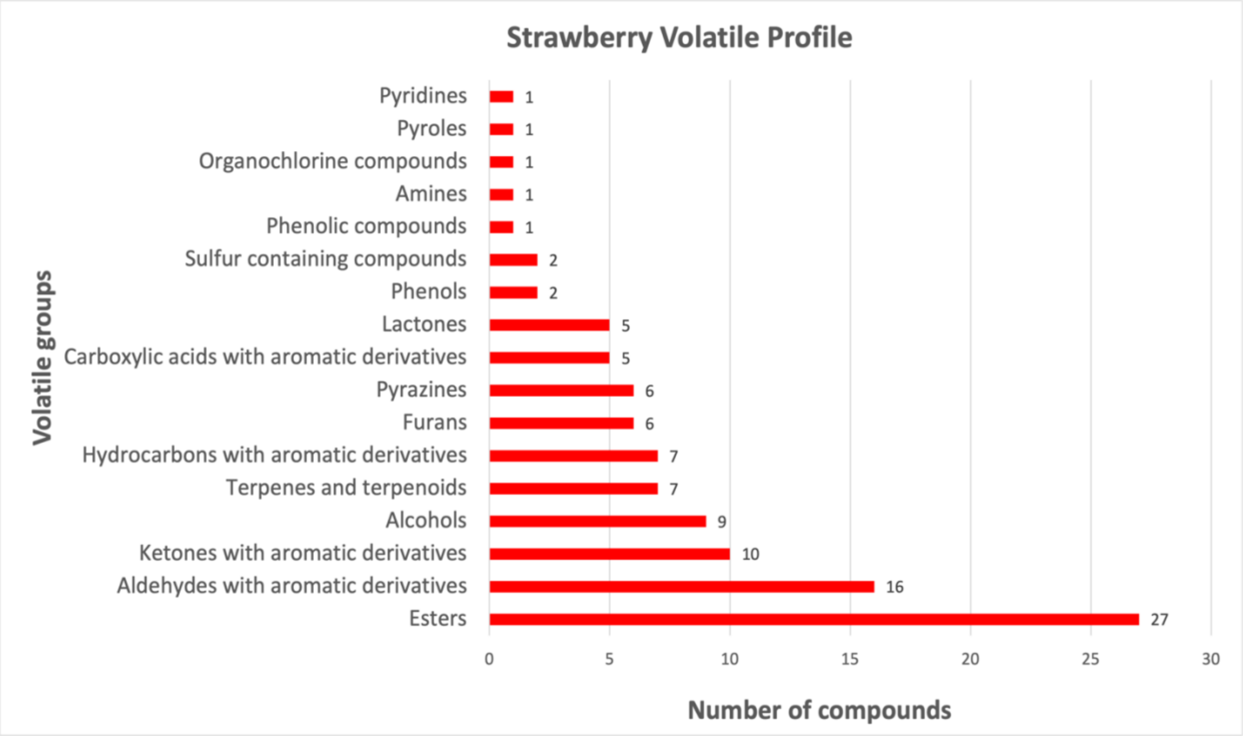


Figure 3.7. Volatile profile of strawberry with total number of compounds detected in each chemical group.

As mentioned in Table 3.12, 122 of total volatile compounds were detected in the blueberries by the e-nose and 21, 23, 19, 12, and 14 of these volatile compounds were also reported by Pico et al. (2022), Forney et al. (2022), Farneti et al. (2017), Qian et al. (2022), and Qian et al. (2021), respectively, for various blueberry cultivars. The volatile profile of blueberry is shown in

Figure 3.8 as per compounds detected in each chemical group. Like strawberries, the bulk of blueberry volatiles comprised of 15.57% of alcohols with aromatic derivatives (19 compounds), 14.75% of aldehydes with aromatic derivatives (18 compounds), 13.11% of esters (16 compounds), 9.84% of ketones with aromatic derivatives (12 compounds), 7.38% of furans (9 compounds), 7.38% of terpenes and terpenoids (9 compounds), 4.10% of carboxylic acids (5 compounds), and 3.28% of lactones (4 compounds).

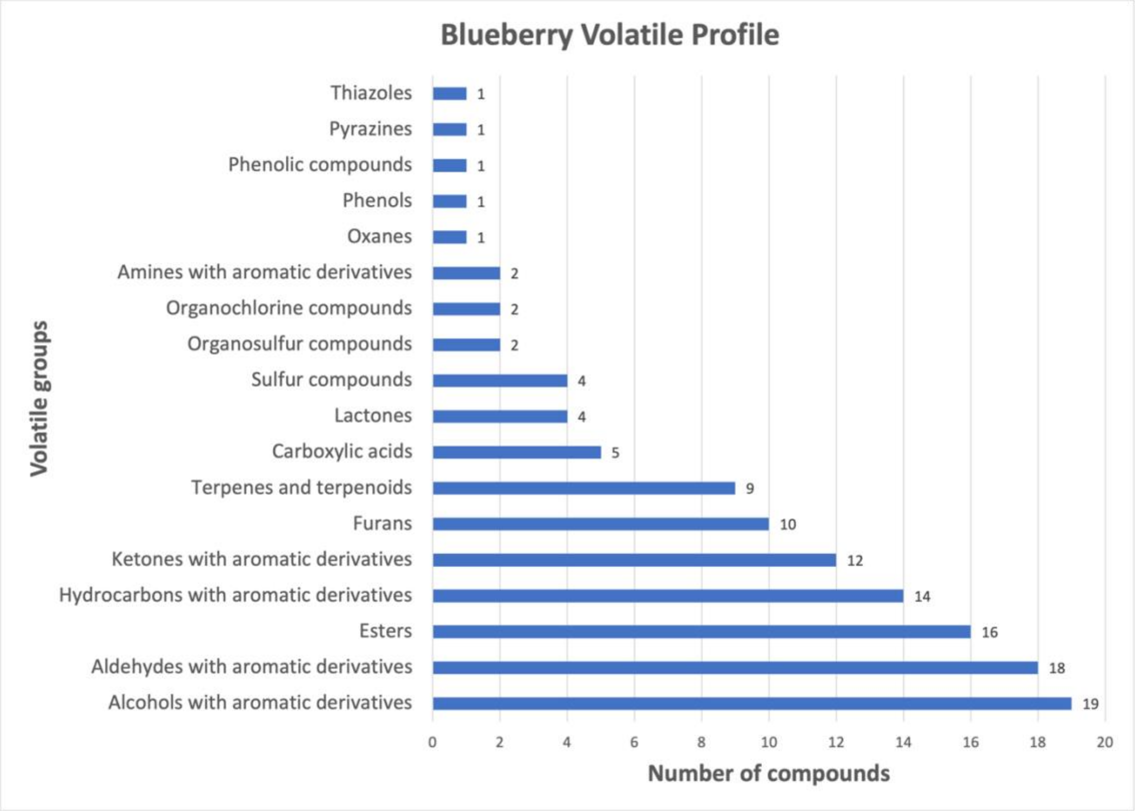


Figure 3.8. Volatile profile of blueberry with total number of compounds detected in each chemical group.

Table 3.11. E-nose detection of volatile aroma compounds present in different strawberries with their intensities indicated as Mean ± SE of triplicate peak areas (*n* = 3).

Kovats RI (Retention Index)	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
	Alcohols (9)				
543	1-propanol	9966.20±4.17	13348.03±1.63	ND	Alcoholic, ethanol, fermented, fruity, fusel, musty, plastic, pungent
567	2-mercaptoethanol	145.04±0.87	ND	ND	Strong, sulfurous
626	2-methyl-1-Propanol	ND	ND	1933.79±2.24	Alcoholic, bitter, chemical, fusel, glue, leek, licorice, musty, oil, solvent, sweet, winey
684	Pent-1-en-3-ol	1215.15±1.71	1341.05±1.11	1759.44±2.73	Burnt, butter, fruity, grassy, green, horseradish, meaty, milky, pungent, tropical, vegetable
703	3-pentanol	ND	ND	75.72±0.96	Fruity, green, nutty, oily, sweet
846	4-Methylpentanol [1]	812.76±1.51	ND	ND	Fruity, green, herbaceous, nutty, oily, yeasty fermented
852	(Z)-3-hexen-1-ol	996.56±2.78	ND	1253.09±1.88	Earthy, floral, fresh, fruity, green, leafy, mossy, oily, petal
861	Cis-3-Hexenol [1]	50172.03±8.95	57225.35±7.57	68700.63±6.68	characteristic, fresh, fruity, grassy, green, leafy, melon, oily, pungent, strong, vegetable
869	(Z)-2-Hexen-1-ol	ND	922.46±1.04	4866.07±3.31	Caramelized, fruity, green, leafy, winey
	Aldehydes (15)				
434	Acetaldehyde [1]	3393.42±2.63	2748.43±1.24	3157.97±2.98	Aldehydic, etheral, fresh, fruity, pleasant, pungent
451	Propanal	1861.11±1.69	734.34±1.43	1596.61±2.18	Acetaldehyde, cocoa, earthy, etheral, nutty, plastic, pungent, solvent
578	Butanal	ND	312.30	ND	Chocolate, cocoa, green, malty, musty, pungent
662	2-methylbutanal	ND	ND	7780.00±1.92	Almond, apple, burnt, burnt (strong), choking, cocoa, coffee, fermented, fruity, green, iodoform, malty, musty, nutty, powerful, sour
700	Pentanal [1]	1635.48±1.33	1254.22±2.05	ND	Acrid, almond, berry, fermented, fruity, green, herbaceous, malty, nutty, pungent, rubber
750	(E)-2-pentenal [1]	ND	ND	585.98±1.59	Apple, fruity, green, oily, orange, pungent, soapy, strawberry, tomato
754	2-Methylpentanal	423.14±0.89	ND	ND	Cheese, earthy, etheral, fruity, green
756	Methyl crotonal	ND	ND	51.36±0.94	Fruity, green, sharp
800	(Z)-3-hexenal [1]	37206.98±4.95	31596.40±5.00	46929.08±7.80	Acron, apple, fatty, fruity, grassy, green, leafy

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
911	(E,E)-2,4-hexadienal [1]	1163.89±1.16	1156.37±1.10	ND	Citrus, floral, green, spicy, sweet, vegetable
907	Methional [1]	ND	ND	586.43±1.20	Baked potato, creamy, earthy, grassy, musty, potato, potato (cooked), tomato, vegetable
1045	(Z)-2-octenal	149.36±1.03	740.81±1.77	398.02±0.99	Earthy, fatty, fruity, green, leafy, walnut
1111	n-Nonanal [1]	436.85±1.13	1018.96±1.69	ND	Aldehydic, chlorine, citrus, fatty, floral, fresh, fruity, gaseous, gravy, green, lavender, melon, orange, orange peel, orris, peely, pungent (slightly), rose, soapy, sweet, tallowy, waxy
1307	Undecanal [1]	ND	65.98±1.24	ND	Aldehydic, citrus, fatty, floral, fresh, fruity, green, oily, pungent, soapy, sweet, waxy
1409	Dodecanal [1]	ND	ND	301.31±2.40	Aldehydic, caprylic, citrus, fatty, floral, green, herbaceous, lily, oily, soapy, waxy
	Aromatic aldehydes (1)				
1305	Cinnamaldehyde [1]	ND	ND	161.19±0.95	Cinnamon, clove, pungent, spicy, sweet, warm
	Amines (1)				
403	Trimethylamine	179.02±1.56	190.77±0.93	289.68±1.38	Alcoholic, ethanol, pungent, strong, sweet, weak
	Carboxylic acids (4)				
619	Acetic acid [1]	10326.57±3.61	ND	649.48±1.73	Acetic, acidic, odorless, pungent, sharp, sour, vinegar
867	2-methylbutanoic acid [2,3]	564.58±2.65	ND	ND	Cashew, cheese, cheese (roquefort), fruit (overripe), pungent, sweaty, sweet
906	Pentanoic acid [1]	1377.51±1.47	59.88±0.91	2906.59±1.98	Acidic, beefy, cheese, penetrating, pungent, putrid, rancid, sour, sweaty
990	Hexanoic acid [1,2,3]	ND	914.40±1.04	ND	Cheese, fatty, goat, pungent, rancid, sour, sweaty
	Aromatic carboxylic acids (1)				
1440	(E)-Cinnamic acid [3]	ND	ND	51.66±0.82	Floral, honey, sweet, woody
	Esters (27)				
489	Methyl acetate	14824.34±4.33	25845.85±3.96	32337.08±2.28	Blackcurrant, etheral, fragrant, fruity, fruity (sweet), pleasant, solvent, sweet
612	Ethyl Acetate	ND	2458.92±1.29	5416.49±1.10	Acidic, butter, caramelized, etheral, fruity, green, orange, pineapple, pungent, solvent, sweet

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
626	Methyl propanoate	ND	ND	2601.75±1.72	Apple, etheral, fresh, fruity, harsh, rum, strawberry, sweet
651	Isopropyl acetate [1]	1368.24±1.17	ND	ND	Banana, chemical, etheral, fruity, sweet
714	Propyl acetate [1]	9617.54±1.84	61975.06±4.43	69649.22±8.14	Caramelized, celery, fermented, fruity, fusel, ketonic, mild, pear, raspberry, sovent, sweet
756	Ethyl isobutyrate	ND	ND	243.86±1.55	Alcoholic, etheral (sweet), fruity, fusel, rubber, strawberry, sweet
772	Methyl 2-methylbutanoate	184.14±1.20	627.61±1.59	ND	Apple, chewing gum, fatty, green, lily, powdery, solvent, spirit,
813	Butyl acetate [1]	2077.13±0.83	14458.93±5.28	ND	Banana, bitter, etheral, fruity, green, pear, pineapple, pleasant, solvent, strong, sweaty, sweet
823	Methyl pentanoate [1]	ND	ND	2869.08±2.86	Apple, etheral, fruity, green, nutty, pineapple, sweet
849	Ethyl 2-methylbutyrate	2941.83±1.51	3316.65±2.38	2430.39±2.26	Apple, blackberry, cognac, fruity, green, phenolic, sharp, strawberry, sweet
900	Ethyl pentanoate	620.93±1.55	ND	ND	Apple, fruity, fruity (sweet), grassy, green, minty, orange, pineapple, sweet, tropical, yeasty
924	Methyl hexanoate [1,2,3]	ND	1863.29±1.03	ND	Acetone, fresh, fruity, pineapple, sweet, thinner
972	Amyl propanoate	ND	ND	1128.39±2.90	Apricot, fruity, fruity (sweet), pineapple, sweet, sweet (very)
999	Ethyl hexanoate [1,2,3]	ND	6479.55±1.65	917.07±1.36	Anise, apple, banana, berry, fruity, fruity (sweet), green, pineapple, strawberry, sweaty, sweet, unripe, waxy, wine gum
1098	Butyl pentanoate	ND	ND	636.56±1.67	Apple, etheral, fruity, fruity (sweet), green, pineapple, raspberry, sweet, tropical
1106	Ethyl 3-(methylthio)propanoate	58.56±1.07	ND	ND	Fruity, metallic, pineapple, sulfurous, tomato
1016	Trans-hex-2-enyl acetate [2]	ND	7633.33±3.96	ND	Apple, banana, fresh, green, sweet, waxy
1150	Hexyl isobutyrate [1]	63.61±1.08	ND	ND	Apple, berry, fruity, grape, green, pear, sweet
1194	(E)-2-Hexen-1-ol, butanoate	404.23±1.03	571.32±1.56	ND	Apple, apricot, banana, banana (ripe), cheese, fermented, fruity, green, meaty,
1200	Methyl salicylate [1]	ND	ND	311.41±1.04	Berry, minty, peppermint, sweet, warm, winey, wintergreen
1392	Octyl butanoate	1154.33±0.97	1625.23±1.84	ND	Creamy, earthy, fresh, fruity, green, herbaceous, oily, waxy

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
1433	Octyl crotonate	290.05±1.12	394.67±1.98	241.57±0.87	Chemical, fruity, harsh, hay, mushroom, winey
1470	Pentyl octanoate	ND	51.60±0.83	ND	Cognac, fatty, orris, sweet, winey
1532	Methyl dodecanoate [1]	ND	ND	78.65±0.82	Coconut, creamy, fatty, floral, fruity, mushroom, soapy, sweet, waxy, waxy (weak)
1580	Hexyl octanoate	ND	ND	155.29±1.97	Apple, berry, ester, fruity, green, herbaceous, oil, waxy
1592	Propyl cinnamate	239.58±1.39	ND	ND	Peach
1597	Decyl butanoate	ND	233.14±1.06	ND	Fruity, fruity (sweet), rose, sweet, waxy
	Furans (6)				
893	2-butylfuran	143.74±1.11	183.22±1.57	312.79±2.25	Fruity, mild, spicy, sweet, weak
919	2-(5H)-furanone [1]	ND	320.98±1.63	237.95±1.95	Butter
979	5-methylfurfural [1]	193.48±2.50	290.33±1.49	396.18±2.63	Acidic, almond, burnt sugar, caramelized, coffee, maple, spicy
1140	2-Ethyl-4-hydroxy-5-methyl-3(2H)-furanone/ Homofuraneol	ND	ND	397.07±1.07	Butterscotch, candy, caramelized, sweet
1067	4-hydroxy-2,5-dimethyl-3(2H)-furanone/ Furaneol [1,2,3]	543.52±2.19	588.65±2.32	512.94±1.74	Baked, burnt sugar, candy, caramelized, cotton candy, strawberry, sweet
1196	5-ethyl-3-hydroxy-4-methyl-2(5H)-furanone	ND	ND	82.12±0.99	Brown sugar, butterscotch, caramelized, fruity, fruity (sweet), maple, nutty, seasoning, spicy, sweet
	Hydrocarbons (2)				
787	Cyclopentane, 1-ethyl-3-methyl-	67.02±0.85	ND	ND	Pungent, synthetic
1645	8-methyl hexadecane	67.68±1.16	ND	ND	N/A
	Aromatic hydrocarbons (5)				
563	Cyclopentane	2617.57±2.25	ND	ND	Mild, sweet
732	Methylcyclohexane	391.67±0.90	429.26±1.97	ND	Faint, fruity, sweet
994	1,3,5-trimethylbenzene/ Mesitylene	ND	ND	5682.55±3.57	Aromatic, herbaceous

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
1030	1-Methyl-4-isopropenyl-1-cyclohexene	ND	ND	616.59±1.21	Citrus, etheral, fruity, green, lemon, licorice, orange, pleasant
1519	Myristicin [1]	ND	ND	61.61±0.89	Balsamic, mild, spciy, warm, woody
	Ketones (8)				
581	3-Buten-2-one	ND	2569.77±3.53	ND	Pungent, synthetic
594	Butan-2-one	ND	ND	383.08±1.10	Acetone, butter, cheese, chemical, chocolate, etheral, fragrant, fruity, gaseous, pleasant, pungent, sharp, sweet
654	1-Hydroxy-2-propanone	519.68±1.31	642.79±1.49	ND	Caramelized, pungent, sweet
699	3-hydroxy-2-butanone/Acetoin [1]	236.76±0.87	ND	2043.60±2.48	Butter, coffee, creamy, dairy, fatty, milky, sweet, woody
791	Hexan-2-one	ND	ND	2403.41±2.29	Acetone, cinnamon, etheral, fruity, fungal, ketonic, meaty, pungent
880	3-mercapto-4-methyl-2-pentanone	3090.38±1.92	2094.65±1.28	1467.04±1.52	Blackcurrant
888	3-Heptanone	ND	1015.37±1.31	ND	Cinnamon, fatty, fruity, green, spicy, sweet
1496	2-Tridecanone [1]	ND	86.40±0.95	ND	Coconut, dairy, earthy, fatty, fruity, green, herbaceous, milky, nutty, rancid, spicy, tallowy, waxy
	Aromatic Ketones (2)				
1487	Coumarin [1]	239.58±1.87	ND	ND	Fragrant, green, hay, pleasant, sweet, tonka broadbean, vanilla
1636	Benzophenone	ND	ND	50.23±0.97	Balsamic, geranium, metallic, powdery, powdery (faint), rose
	Lactones (5)				
1084	δ-Hexalactone [1]	ND	356.36±2.02	ND	Coconut, creamy, fruity
1407	δ-Nonalactone	96.69±1.85	ND	ND	Coconut, coumarin, creamy, milky, sweet
1471	γ-Decalactone [1,3]	ND	ND	57.11±2.86	Coconut, fatty, fresh, fruity (dried), lactone, oily, oily (fresh), peach, sweet, waxy
1614	δ-Undecalactone	ND	ND	53.71±1.03	Coconut, creamy, fatty, fruity, peach, waxy
1660	(Z)-Dodec-6-en-4-olide	ND	59.17±0.96	ND	Creamy, dairy, fatty, floral, fruity, peach, sweet, waxy

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
	Organochlorine compounds (1)				
645	Trichloroethane	ND	2291.94±1.29	ND	Chloroform, etheral, mild, sweet
	Phenols (2)				
1054	2-Methyl phenol [1]	ND	196.35±2.33	ND	Musty, phenolic, sweet
1316	4-vinylguaiacol	63.63±0.85	ND	ND	Amber, clove, curry, dry, fresh, peanut, phenolic, smoky, woody, woody (dry)
	Phenolic compounds (1)				
1555	Rheosmin	75.10±1.78	ND	ND	Balsamic, berry, floral, fruity, fruity (sweet), jam, raspberry, sweet, warm
	Pyrroles (1)				
757	Pyrrole [1]	62.54±1.40	128.92±2.05	ND	Chloroform, coffee, cracker, nutty, sweet, warm
	Pyrazines (6)				
1004	2-Ethyl-3-methylpyrazine	2448.29±2.76	ND	ND	Balsamic, bread, corn, earthy, musty, nutty, peanut, roast
1081	2-Ethyl-3,6-dimethylpyrazine	191.31±1.19	150.36±1.41	ND	Burnt, cocoa, earthy, musty, nutty, potato, pungent, roast
1083	2-Ethyl-3,5-dimethylpyrazine	ND	ND	628.53±2.66	Chocolate, cocoa, musty, nutty, potato, sweet, woody
1097	2-Isopropyl-3-methoxypyrazine	151.80±1.12	ND	ND	Beany, bell pepper, dry, earthy, grassy, green, pea
1158	2,3-Diethyl-5-methylpyrazine	ND	93.32±0.85	ND	Fragrant, hazelnut, meaty, musty, nutty, potato, roast, sweet, vegetable
1183	2-Isobutyl-3-methoxypyrazine	ND	88.09±0.96	ND	Bell pepper, dry, earthy, green, green pepper, leafy, pea, pepper, spicy
	Pyridines (1)				
1202	2-Pentyl-pyridine	793.62±1.81	1212.57±2.30	ND	Fatty, green, green pepper, mushroom, pepper, tallowy
	Sulfur compounds (2)				
516	Methanethiol [1]	ND	ND	82851.84±3.68	Earthy, fruity, garlic, garlic (penetrating), leek, onion, rubber, skunk (strong), strong, sulfurous
839	Dimethyl sulfoxide [1]	ND	ND	143.57±1.36	Alliaceous, fatty, garlic, mushroom, oily, sulfurous

Table 3.11. *Continued.*

Kovats RI	Compounds	Commercially Grown Strawberries available in the United States			Sensory Descriptors
		SB1	SB2	SB3	
	Terpenes (4)				
936	1S-()-a-pinene	ND	ND	1315.63±3.96	Fresh, herbaceous, pine, resinous, sharp, terpenic, turpentine, warm
937	α-Pinene [1]	837.97±2.88	ND	ND	Camphor, citrus, earthy, fresh, fruity, green, lime, pine, sweet, terpenic, turpentine, woody
991	Myrcene [1]	ND	ND	162.18±1.37	Balsamic, etheral, fruity, geranium, lemon, metallic, musty, plastic, pleasant, resinous, soapy, spicy, sweet, woody
1025	p-Cymene	3341.20±4.68	ND	ND	Aromatic, balsamic, citrus, fresh, fruity, fuel, gasoline, herbaceous, lemon, mild, pleasant, solvent, spicy, sweet, weak, woody
	Terpenoids (3)				
1148	Citronellal	120.59±2.46	291.79±1.28	ND	Aldehydic, citrus, dry, fatty, floral, fruity, green, lemon, peper, rose, sweet, waxy
1189	α-Terpineol [1]	308.78±1.66	ND	236.64±1.50	Anise, citrus, floral, fruity, lilac, minty, oily, peach, pine, toothpaste, woody
1402	Methyl eugenol [1]	ND	90.60±1.02	ND	Carnation, cinnamon, clove, fresh, mild, spicy, sweet, warm

ND = Not Detected; N/A = Not Available;

[1] GC-MS (Gas Chromatography – Mass Spectrometry) detection by Cannon et al. (2015);

[2] GC-FID (Gas Chromatography – Flame Ionization Detector) detection by González-Domínguez et al. (2020);

[3] GC-MS (Gas Chromatography – Mass Spectrometry) detection by Passa et al. (2023).

Table 3.12. E-nose detection of volatile aroma compounds present in different blueberries with their intensities indicated as Mean±SE of triplicate peak areas (*n* = 3).

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
	Alcohols (16)						
510	2-Propanol	ND	ND	1342.56±3.28	ND	ND	Acetone, alcoholic, ethanol, etheral, musty, pleasant, rubbing alcohol, woody
543	1-Propanol [1]	1216.54±4.72	727.99±2.89	ND	ND	606.37±4.76	Alcoholic, ethanol, fermented, fruity, fusel, musty, plastic, pungent
594	2-Butanol [2]	ND	63.13±1.06	73.32±1.12	ND	ND	Pleasant, strong, sweet, wine
626	2-Methyl 1-propanol [1]	388.72±1.87	ND	246.16±2.93	ND	ND	Alcoholic, bitter, chemical, fusel, glue, leek, licorice, musty, oil, solvent, sweet, winey
691	Pentan-2-ol	ND	205.27±4.22	ND	270.56±2.95	748.09±1.61	Alcoholic, etheral, fermented, fruity, fusel, green, green (mild), mild, nutty, oil, plastic, pungent, raspberry, sweet
703	3-Pentanol	ND	181.69±4.28	96.96±1.16	ND	496.21±3.05	Fruity, green, nutty, oily, sweet
746	Propylenglycol	ND	ND	ND	ND	137.95±1.01	Alcoholic, caramelized, odorless
767	Pentanol [3]	176.80±2.27	94.27±1.03	ND	227.52±4.22	186.94±1.07	Alcoholic, anise, balsamic, fruity, fusel, green, mild, oil, pungent, sweet, waxy
801	2-Hexanol [1]	5601.45±3.31	12783.92±7.83	6296.39±3.91	60826.44±6.05	70695.71±5.09	Cauliflower, chemical, fatty, fruity, terpenic, winey
788	2,3-Butanediol	ND	ND	ND	750.48±2.03	ND	Creamy, fruity, odorless, onion
852	(Z)-3-Hexen-1-ol [2,3,5]	ND	ND	ND	1463.30±1.04	1164.74±1.99	Earthy, floral, fresh, fruity, green, leafy, mossy, oily, petal
861	Z-3-Hexenol [4]	19079.45±3.09	26763.07±2.62	10406.17±4.86	75718.22±8.64	64190.28±8.02	Fresh, fruity, grassy, green, leafy, melon, oily, vegetable
870	1-Hexanol [1,2,4]	59797.25±5.29	39889.61±4.06	15435.98±3.96	ND	ND	Alcoholic, dry, fatty, floral, fruity, fusel, grassy, green, hay, herbaceous, leafy, oil, pleasant, resinous, sharp, sweet, toasty, woody (mild)
1473	1-Dodecanol	52.33±1.06	ND	ND	ND	ND	Coconut, earthy, fatty, honey, soapy, waxy
1500	2-Tridecanol	ND	ND	ND	115.87±2.41	ND	Fruity (sweet)
1676	1-Tetradecanol	56.10±4.17	ND	ND	ND	ND	Coconut, oily fatty (weak)
	Aromatic alcohols (3)						
1036	Benzyl alcohol [1,3,4,5]	ND	ND	ND	311.47±2.28	202.86±1.62	Aromatic, balsamic, faint, floral, fruity, phenolic, rose, sweet
1116	2-Phenylethanol	ND	ND	111.75±1.24	ND	ND	Floral, flower, honey, lilac, perfumery, rose, spicy
1183	Cymen-8-ol [2]	106.98±2.94	ND	ND	ND	ND	Cherry, citrus, coumarin, floral, fruity (sweet), musty, sweet

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
	Aldehydes (15)						
434	Acetaldehyde	13726.95±6.59	13886.91±7.29	20597.58±6.41	12942.51±4.82	14466.14±5.39	Aldehydic, etheral, fresh, fruity, pleasant, pungent
451	Propanal	10400.98±4.16	9919.36±1.93	15074.31±4.29	1607.75±1.38	599.10±1.29	Cocoa, earthy, etheral, nutty, plastic, pungent, solvent
522	2-methylpropanal	ND	ND	ND	347.80±2.85	1135.16±3.67	Aldehydic, baked potato, burnt, floral, fresh, fruity, green, malty, pungent, sharp, spicy, toasted
578	Butanal	593.67±2.00	ND	ND	ND	ND	Chocolate, cocoa, green, malty, musty, pungent
652	3-methyl butanal [2,3]	182.18±1.83	ND	ND	ND	ND	Aldehydic, almond, apple, cheese, chocolate, fatty, fruity, green, herbaceous, malty, peach, toasted
750	(E)-2-pentenal [2,3,5]	ND	ND	52.92±1.89	ND	ND	Apple, fruity, green, oily, orange, pungent, soapy, strawberry, tomato
911	(E,E)-2,4-hexadienal [2,3]	493.22±2.12	390.47±1.48	295.91±1.31	134.05±1.12	1471.26±2.89	Citrus, floral, green, spicy, sweet, vegetable
907	Methional [5]	635.46±1.48	ND	ND	ND	285.75±2.28	Baked potato, creamy, earthy, grassy, musty, potato, potato (cooked), tomato, vegetable
958	(E)-2-heptenal [2,3]	ND	ND	ND	ND	1449.91±3.09	Almond, earthy, fatty, fresh, fruity, grassy, green, mushroom, onion, pesticide, plastic, pungent, soap, soapy, sulfurous, tallowy, vegetable, vinegar
1045	(Z)-2-octenal	ND	687.88±1.39	324.48±1.43	1507.10±1.52	1422.12±1.66	Earthy, fatty, fruity, green, leafy, walnut
1111	n-Nonanal [1,2,4,5]	300.32±1.82	466.17±0.89	ND	615.53±3.15	1047.96±1.38	Citrus, fatty, floral, fresh, fruity, gravy, green, lavender, melon, orange, orange peel, orris, pungent (slightly), rose, soapy, sweet, tallowy, waxy
1216	(E, E)-2,4-nonadienal [1]	126.75±0.99	ND	ND	942.31±1.29	831.65±2.74	Cereal, cucumber, deep-fried, fatty, fried, green, melon, oily, potato, soapy, tropical, violet, watermelon, waxy, wool (wet)
1265	2-decenal	ND	ND	ND	ND	52.01±0.92	Aldehydic, fatty, floral, green, orange, rose
1317	2,4-decadienal, (E,E)-	ND	ND	ND	235.60±2.19	ND	Aldehydic, citrus, cucumber, deep-fried, fatty, fried, green, melon, oily, potato, pungent, waxy
1613	Tetradecanal	55.74±1.42	66.51±0.97	ND	ND	ND	Amber, citrus, dry, fatty, floral, musk, waxy
	Aromatic aldehydes (3)						
1045	Benzeneacetaldehyde [5]	ND	ND	ND	945.96±1.93	ND	Cocoa, floral, grassy, green, hawthorn, honey, hyacinth, rose, sweet
1250	p-Anisaldehyde	ND	ND	117.91±0.94	ND	ND	Anise, floral, hawthorn, minty, powdery, sweet

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
1269	(E)-Cinnamaldehyde [5]	ND	92.61±0.88	96.17±1.06	ND	ND	Apple, candy, cinnamon, paint, pungent, rose, spicy, strong, sweet, warm
	Amines (1)						
403	Trimethylamine	384.77±2.17	393.19±1.31	388.57±1.82	504.40±2.09	539.43±2.82	Alcoholic, ethanol, pungent, strong, sweet, weak
	Aromatic amines (1)						
978	Aniline	239.69±1.28	311.18±2.09	157.13±1.37	1686.91±3.01	ND	Amine, aromatic, pleasant, pungent, sweet
	Carboxylic acids (5)						
619	Acetic acid	ND	ND	ND	57.13±0.86	ND	Acetic, acidic, odorless, pungent, sharp, sour, vinegar
816	Butanoic acid	262.50±2.04	333.81±1.99	210.03±1.21	ND	ND	Butter, cheese, penetrating, rancid, sharp, sweaty
860	3-methylbutanoic acid	ND	405.44±1.86	ND	ND	ND	Acidic, cheese, fruity, rancid, sharp, sour, sweaty, tropical
906	Pentanoic acid	ND	ND	131.94±0.72	ND	ND	Acidic, beefy, cheese, penetrating, pungent, putrid, rancid, sour, sweaty
990	Hexanoic acid [1,3]	ND	487.93±2.97	ND	ND	ND	Cheese, fatty, goat, pungent, rancid, sour, sweaty
	Esters (16)						
489	Methyl acetate [2,3]	1261.40±4.01	1375.29±3.99	1186.34±2.19	ND	ND	Blackcurrant, etheral, fragrant, fruity, fruity (sweet), pleasant, solvent, sweet
612	Ethyl Acetate [2,3]	ND	729.17±2.58	ND	ND	ND	Acidic, butter, caramelized, etheral, fruity, green, orange, pineapple, pungent, solvent, sweet
685	Methyl isobutyrate	238.11±1.60	286.02±2.44	ND	616.47±1.29	ND	Apple, floral, fruity, pineapple, sweet
714	Propyl acetate	71.25±1.83	ND	ND	ND	ND	Caramelized, celery, fermented, fruity, pear, raspberry, sweet
755	Methyl but-2-enoate	66.96±0.66	ND	ND	156.81±2.27	ND	Blackcurrant, fruity
772	Methyl 2-methylbutanoate	5360.15±3.04	ND	1136.22±1.53	354.42±0.65	ND	Apple, chewing gum, fatty, green, lily, powdery, solvent, spirit
999	Ethyl hexanoate [3,4]	920.98±2.92	ND	ND	ND	ND	Anise, apple, banana, berry, fruity, fruity (sweet), green, pineapple, strawberry, sweaty, sweet, unripe, waxy, wine gum
1001	Propyl pentanoate	ND	ND	ND	183.63±2.30	ND	Animal, etheral, fruity, metallic, pineapple
1022	Methyl heptanoate	2276.64±1.88	ND	ND	ND	ND	Berry, floral, fruity, green, orris, sweet, waxy

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
1196	Ethyl Octanoate	ND	97.69±1.29	ND	ND	ND	Anise, apple, baked fruity, fatty, fermented, floral, fresh, fruity, green, leafy, mentholic, soapy, sweet, waxy, winey
1199	Propyl heptanoate	ND	94.44±2.40	ND	ND	ND	Apple, fruity, grape, green, pear, pineapple, strawberry, sweet, winey
1292	Butyl heptanoate	ND	250.61±4.29	ND	ND	ND	Fresh, fruity, grassy, green, licorice, oily, pear, tropical, winey
1388	Butyl octanoate	ND	60.97±1.98	ND	ND	ND	Butter, floral, fruity, green, oily
1392	Octyl butanoate	ND	111.94±1.41	ND	ND	ND	Creamy, earthy, fresh, fruity, green, herbaceous, oily, waxy
1490	Ethyl cinnamate	89.07±1.01	ND	ND	ND	ND	Balsamic, berry, cinnamon, floral, fruity, honey, plum, powdery, spicy, sweet
1532	Methyl dodecanoate	74.22±2.79	ND	ND	ND	ND	Coconut, creamy, fatty, floral, fruity, mushroom, soapy, sweet, waxy, waxy (weak)
	Furans (10)						
614	3-methylfuran	ND	ND	ND	ND	120.4±1.10	N/A
604	2-methylfuran	1707.36±4.67	1102.70±2.09	761.76±1.40	170.29±1.38	176.23±2.05	Acetone, burnt, chocolate, gassy (sweet), metallic, musty, solvent
703	2-ethyl furan [2]	ND	ND	ND	809.15±3.35	ND	Acidic, burnt, burnt (sweet), chemical, earthy, malty, pungent, rubber, sweet
893	2-butylfuran	ND	84.28±1.02	ND	306.57±2.00	117.56±8.25	Fruity, mild, spicy, sweet, weak
919	2-(5H)-furanone	251.88±4.63	683.42±5.29	345.91±1.44	1778.17±1.99	ND	Butter
979	5-methylfurfural	ND	311.05±1.07	ND	ND	388.65±0.99	Acidic, almond, burnt sugar, caramelized, coffee, maple, spicy
1049	4-hydroxy-5-methyl-3(2H)-furanone	ND	ND	ND	ND	203.09±3.52	Balsamic, candy, caramelized, cotton candy, sweet
1059	5-ethyldihydro-2(3H)-furanone	ND	ND	ND	261.18±0.93	ND	Coconut, coumarin, sweet, tobacco, tonka broadbean
1067	4-hydroxy-2,5-dimethyl-3(2H)-furanone [6]	56.13±1.52	61.04±2.37	126.92±3.66	311.90±3.04	296.75±1.20	Baked, burnt sugar, candy, caramelized, cotton candy, strawberry, sweet
1196	5-ethyl-3-hydroxy-4-methyl-2(5H)-furanone	ND	59.35±1.46	76.63±1.80	ND	ND	Brown sugar, butterscotch, caramelized, fruity, fruity (sweet), maple, nutty, seasoning, spicy, sweet

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
	Hydrocarbons (9)						
521	1,1-dichloroethene	ND	ND	ND	1062.13±2.03	ND	Chloroform, mild, sweet
699	Trichloroethylene	ND	ND	ND	654.55±1.44	ND	Chloroform, etheral, sweet
700	Heptane	129.56±3.49	87.82±0.95	67.09±1.47	ND	ND	Alkane, fruity, gasoline, sweet
900	Nonane	77.06±1.49	ND	ND	ND	ND	Alkane, fusel, gasoline
1091	1,2-dibromo-3-chloropropane	ND	ND	ND	ND	941.01±2.66	Pungent
1300	Tridecane	289.66±1.04	ND	183.70±2.14	ND	321.15±1.92	Alkane, citrus, fruity, fusel, hydrocarbon
1396	E-Tetradec-7-ene	104.84±1.70	ND	ND	ND	ND	Green
1645	8-methyl hexadecane	ND	ND	ND	ND	53.89±0.81	N/A
1650	6-methyl hexadecane	ND	ND	ND	ND	59.11±0.76	N/A
	Aromatic hydrocarbons (5)						
546	tert-butyl methyl ether	ND	ND	1339.97±4.03	ND	ND	Minty, terpenic
626	Methylcyclopentane	ND	ND	ND	196.97±2.35	ND	Gasoline
664	Cyclohexane	ND	108.66±1.16	544.93±4.27	ND	ND	Chloroform
732	Methylcyclohexane	ND	ND	ND	81.57	ND	Faint, fruity, sweet
1030	1-Methyl-4-isopropenyl-1-cyclohexene	ND	ND	307.23±1.86	ND	ND	Citrus, etheral, fruity, green, lemon, licorice, orange, pleasant
	Ketones (10)						
580	Butane-2,3-dione [5]	98.46±1.32	211.89±1.89	ND	ND	56.06±0.91	Butter, caramelized, chlorine, creamy, fruity, pineapple, spirit, strong, sweet
654	1-Hydroxy-2-propanone	161.20±1.24	ND	ND	271.95±2.86	429.91±1.15	Caramelized, pungent, sweet
688	pentan-2-one	1750.47±4.49	ND	ND	ND	ND	Acetone, banana, etheral, fruity, fruity (sweet), sweet, thinner, woody
699	Acetoin	ND	ND	86.58±1.42	ND	312.75±2.13	Butter, coffee, creamy, dairy, fatty, milky, sweet, woody

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
698	2,3-pentanedione [3]	ND	ND	ND	ND	935.29±1.75	Almond, apple, burnt, butter, butterscotch, caramelized, cheese, creamy, diacetyl, fresh, fruity, grain, malty, nutty, oily, pungent, sweet
786	Cyclopentanone	ND	1034.22±2.68	ND	ND	618.75±2.12	Minty, peppermint
880	3-mercapto-4-methyl-2-pentanone	ND	ND	ND	5002.46±6.80	4547.44±2.88	Blackcurrant
937	3-Hepten-2-one	ND	ND	ND	ND	50.87±0.85	Caraway, grassy, green
986	3-Octanone	ND	ND	ND	1132.17±1.76	ND	Butter, fresh, fruity, herbaceous, lavender, mild, mushroom, resinous, sweet
1293	2-Undecanone [1,2,3]	88.39±0.99	ND	ND	ND	ND	Creamy, dusty, fatty, floral, fresh, fruity, green, ketonic, musty, orange, orris, rose, strong, tallowy, waxy
	Aromatic Ketones (2)						
1065	Acetophenone [2,3]	ND	492.30±1.20	ND	ND	ND	Almond, cheese, chemical, floral, glue, hawthorn, jasmine, musty, orange, orange blossom, pungent, sweet
1636	Benzophenone	ND	ND	64.82±0.94	ND	ND	Balsamic, geranium, metallic, powdery, powdery (faint), rose
	Lactones (4)						
958	γ-Valerolactone	ND	118.46±2.11	ND	ND	ND	Anise, cocoa, herbaceous, sweet, tobacco, warm, woody
1084	δ-Hexalactone	ND	270.04±1.40	ND	ND	ND	Coconut, creamy, fruity
1469	δ-Decalactone	ND	67.48±1.02	ND	ND	ND	Fruity, fruity (sweet), peach, sweet
1471	γ-Decalactone [5]	ND	ND	92.93±0.86	ND	ND	Coconut, fatty, fresh, fruity (dried), lactone, oily, oily (fresh), peach, sweet, waxy
	Organochlorine compounds (2)						
645	Trichloroethane	ND	115.95±2.42	474.91±2.63	ND	ND	Chloroform, etheral, mild, sweet
1624	Cyclohexanecarbamic acid, N-ethylthio, S-ethyl ester	ND	ND	ND	50.64±1.05	ND	Aromatic

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
	Oxanes (1)						
1127	(2S,4R)-rose oxide /(2S,4R)-4-methyl-2-(2-methylprop-1-en-1-yl)tetrahydro-2H-pyran [1]	ND	ND	ND	969.37±1.44	ND	Floral, rose
	Phenols (1)						
986	Phenol	ND	94.35±2.99	ND	277.93±4.14	ND	Acrid, aromatic, medicinal, phenolic, plastic, rubber, sweet
	Phenolic compounds (1)						
1555	Rheosmin	ND	68.09±1.34	ND	ND	ND	Balsamic, berry, floral, fruity, fruity (sweet), jam, raspberry, sweet, warm
	Pyrazines (1)						
737	Pyrazine	ND	ND	127.93±1.55	ND	ND	Bitter, corn, hazelnut, hazelnuts (roasted), nutty, pungent, strong, sweet
	Sulfur compounds (4)						
516	Ethanethiol	ND	ND	ND	1877.35±3.57	1825.24±2.59	Earthy, fruity, garlic, garlic (penetrating), leek, onion, rubber, skunk (strong), strong, sulfurous
971	3-methyl-3-sulfanylbutanol-1-ol	ND	ND	ND	ND	762.75±1.56	Broth, chervil, meat (cooked), meat broth, onion (cooked), spicy, sweet, tartare, vegetable
839	Dimethyl sulfoxide	ND	ND	ND	ND	924.98±1.05	Alliaceous, fatty, garlic, mushroom, oily, sulfurous
747	Dimethyl disulfide [2]	ND	ND	ND	ND	56.82±0.93	Cabbage, cheese (ripened), garlic, onion, putrid, sulfurous, vegetable
	Organosulfur compounds (2)						
775	2-methylthiophene	ND	ND	ND	276.57±2.48	ND	Alliaceous, gasoline, green, onion, paraffinic, sulfurous, sweet
1501	Tebuthiuron	ND	ND	ND	ND	129.78±2.27	Faint, musty
	Thiazoles (1)						
1021	2-acetylthiazole	ND	247.69±1.71	ND	ND	ND	Bread, burnt, caramelized, cereal, grassy, hazelnut, hazelnut (grilled), nutty, peanut, popcorn, roast, strong, sulfurous, sweaty, taco

Table 3.12. *Continued*.

Kovats RI	Compounds	Commercially Grown Blueberries available in the United States [a]			Locally Cultivated Blueberries Grown at Ambient Temperature (AT)[b] and Elevated Temperature (ET)[c]		Sensory Descriptors
		BB1[a]	BB2 [a]	BB3 [a]	Titan AT [b]	Titan ET [c]	
	Terpenes (3)						
991	β-Myrcene [1,2,4]	ND	ND	254.72±0.92	ND	ND	Balsamic, etheral, fruity, geranium, lemon, metallic, musty, plastic, pleasant, resinous, soapy, spicy, sweet, woody
1004	α-Phellandrene [1,2]	ND	1000.11±1.07	226.72±1.74	ND	308.66±1.66	Citrus, green, minty, spicy, terpenic, turpentine, woody
1048	D-Limonene [1,2,3,4]	1089.88±2.42	ND	ND	ND	861.22±1.84	Citrus, fruity, minty, orange, peely
	Terpenoids (6)						
1099	Linalool [1,2,3,4,5]	270.69±2.77	ND	56.67±1.26	886.92±1.72	ND	Anise, bergamot, citrus, floral, fragrant, fresh, fruity, green, lavender, lemon, lily, muscat, oil, parsley, rose, spicy, sweet, terpenic, woody
1145	Camphor	464.84±2.57	397.17±1.47	312.22±1.20	ND	796.77±1.91	Aromatic, camphor, dry, fragrant, green, leafy
1229	Citronellol [1,4,5]	ND	185.93±0.94	ND	ND	ND	Floral, fresh, rose
1261	(Z)-citral/ Neral [1,4]	70.21±0.81	ND	ND	ND	ND	Citrus, green, fatty, fruity, lemon, musty, oily, peely, strong, sweet
1357	Eugenol [1,3,4,5]	ND	53.85±0.92	ND	ND	ND	Balsamic, camphor, clove, floral, herbaceous, honey, spicy, sweet, warm, woody
1402	Methyl eugenol	ND	ND	87.66±1.69	ND	ND	Carnation, cinnamon, clove, fresh, mild, spicy, sweet, warm

ND = Not Detected; N/A = Not Available;

[1] SPME-GC-MS (Solid Phase Microextraction – Gas Chromatography – Mass Spectrometry) detection by Pico et al. (2022);

[2] GC-TOF-MS (Gas Chromatography – Time of Flight – Mass Spectrometry) detection by Forney et al. (2022);

[3] SPME-GC-MS (Solid Phase Microextraction – Gas Chromatography – Mass Spectrometry) detection by Farneti et al. (2017);

[4] GC-MS (Gas Chromatography – Mass Spectrometry) detection by Qian et al. (2022);

[5] GC-O (Gas Chromatography – Olfactometry) detection by Qian et al. (2021);

[6] GC-O (Gas Chromatography – Olfactometry) detection by Du et al. (2011).

3.4.1. Alcohols

Alcohols consisted of 8.41% of the detected volatile compounds in strawberries. The common presence of cis-3-hexenol (50172.03±8.95–68700.63±6.68) and pent-1-en-3-ol (1215.15±1.71−1759.44±2.73) was observed in all strawberries among total nine alcohols. 2-methyl-1-Propanol (1933.79±2.24) and 3-pentanol (75.72±0.96) were detected only in SB3 strawberries. The sensory descriptors of 2-methyl-1-propanol is described as 'alcoholic, bitter, chemical, fusel, glue, leek, licorice, musty, oil, solvent, sweet, winey', whereas those of 3-pentanol is characterized by 'fruity, green, nutty, oily, sweet' − indicating SB3's aroma uniqueness for the presence of these alcohol volatiles. Two of the nine alcohols detected in this study (4-Methylpentanol, Cis-3-Hexenol) was also reported by Cannon et al. (2015) but the other seven were not identified by them. Despite the abundance of short chain alcohols in strawberry, they usually do not impart aroma because of higher odor thresholds (Jetti et al., 2007). Cannon et al. (2015) detected 4-Methylpentanol and Cis-3-Hexenol in strawberries but rest of the seven alcohols as mentioned in Table 3.11 was not reported by those authors. Although one specific alcohol named (Z)-2-Penten-1-ol was reported by Fan et al. (2021) to enhance consumer perception of sweetness, neither it was detected in this current investigation nor other studies have related sweetness likability of sensory panels to this alcohol.

The nineteen alcohols with aromatic derivatives amounted for 15.57% of the overall volatile aroma profile of blueberries. Z-3-hexenol with characteristic green aroma was present in all samples although its intensity was higher among local Titan AT (75718.22±8.64) and Titan ET (64190.28±8.02) as compared to the commercial BB1, BB2, and BB3 samples (10406.17±4.86–26763.07±2.62). It means that the green aroma perception in the local samples were more prominent than it was for commercial ones. Similarly, (Z)-3-hexen-1-ol with 'earthy, floral, fresh, fruity, green, leafy, mossy, oily, petal' were identified in only the locally-grown samples (134.55±2.95–1463.30±1.04). Additionally, the presence of benzyl alcohol was only detected in locally-grown Titan AT (311.47±2.28) and Titan ET (202.86±1.62) blueberries with 'aromatic, balsamic, faint, floral, fruity, phenolic, rose, sweet' aroma descriptors. However, only the commercial blueberries contained 1-Hexanol (BB1: 59797.25±5.29; BB2: 39889.61±4.06; BB3: 15435.98±3.96) with sensory attributes described as 'alcoholic, dry, fatty, floral, fruity, fusel, grassy, green, hay, herbaceous, leafy, oil, pleasant, resinous, sharp, sweet, toasty, woody (mild)'. These results indicate that the locally cultivated blueberries had a distinct alcohol content than their commercial counterparts. Eight of the alcohols (2-Propanol, Pentan-2-ol, 3-Pentanol, Propylenglycol, 2,3-Butanediol, 1-Dodecanol, 2-Tridecanol, 1-Tetradecanol) and one of the aromatic alcohols (2-Phenylethanol) observed in this study were not previously mentioned by Pico et al. (2022), Qian et al. (2022), Forney et al. (2022), Farneti et al. (2017), or Qian et al. (2021).

3.4.2. Aldehydes

Aldehydes and their aromatic derivatives amounted for 14.95% of total strawberry volatiles. Among all aldehydes identified in this study, (Z)-3-hexenal had relatively larger peak areas within 31596.40±5.00–46929.08±7.80 range followed by acetaldehyde (2748.43±1.24–3393.42±2.63). 'Fresh' and 'green' odors are typical of hexanals such as (Z)-3-hexenal (Schieberle & Hofmann, 1997). These two aldehydes along with propanal and (Z)-2-octenal were detected in all strawberry samples. The aromatic aldehyde Cinnamaldehyde (161.19±0.95) was detected only in SB3 strawberry, indicating SB3 was uniquely characterized with 'cinnamon, clove, pungent, spicy, sweet, warm' sensory descriptors associated with this compound. Nine aldehydes namely acetaldehyde, pentanal, (e)-2-pentenal, (z)-3-hexenal, (e,e)-

2,4-hexadienal, methional, n-nonanal, undecanal, dodecanal previously reported by Cannon et al. (2015) in 'Ciflorette' strawberries were also detected in this study.

The 14.75% of the overall blueberry volatile profile consisted of fifteen aldehydes and three of its aromatic derivatives. Acetaldehyde was identified in all blueberry samples within the range of 12942.51±4.82−20597.58±6.41. Propanal was also detected in all samples but locally grown Titan AT (1607.75±1.38) and Titan ET (599.10±1.29) samples had relatively lower intensities than the commercial BB1 (10400.98±4.16), BB2 (9919.36±1.93), and BB3 (15074.31±4.29) samples. Only BB1 contained butanal (593.67±2.00) and 3-methyl butanal (182.18±1.83) while their presence were not detected in any other sample. All samples had (E,E)-2,4-hexadienal with 'citrus, floral, green, spicy, sweet, vegetable' sensory descriptors identified in them within 134.05±1.12−1471.26±2.89 peak area range.

However, benzeneacetaldehyde with 'cocoa, floral, grassy, green, hawthorn, honey, hyacinth, rose, sweet' sensory descriptors was only found in Titan AT (945.96±1.93) cultivar. These results indicate that locally-grown Titan AT and Titan ET had quite different aldehyde content than other samples. In addition, no aromatic aldehyde was detected in Titan ET which may have happened due to the elevated temperature growing condition of this blueberry sample. Two out of the three aromatic aldehydes reported in this study (benzeneacetaldehyde, (E)-cinnamaldehyde) have been previously detected in highbush varieties such as 'Elliot' and 'Bluecorp' (Qian et al., 2021) but the presence of p-Anisaldehyde was noted in BB3 blueberry sample (117.91±0.94) of this investigation which was not reported by Qian et al. (2021), Farneti et al. (2017), Qian et al. (2022), Forney et al. (2022), or Pico et al. (2022). In addition, seven out of the fifteen aldehydes identified in this study namely Acetaldehyde, propanal, 2-methylpropanal, Butanal, (Z)-2-octenal, (E)-2-decenal, 2-decenal, (E,E)-2,4-decadienal, and Tetradecanal were not reported by the previously-mentioned articles.

3.4.3. Carboxylic acids

Around 4.67% of the strawberry aroma constituents was accounted for carboxylic acids and its aromatic derivatives. SB1 was more potent in acids such as acetic acid (10326.57±3.61), 2-methylbutanoic acid (564.58±2.65), and pentanoic acid (1377.51±1.47) as compared to other samples. However, (E)-cinnamic acid with 'floral, honey, sweet, woody' aroma notes was only detected in SB3 which is indicative of its distinct aroma profile. Carboxylic acids such as hexanoic acid are usually associated with 'cheesy' or 'sweaty' odors that may affect consumer aroma acceptance and sweetness in strawberries (Ulrich & Olbricht, 2016). All of the carboxylic acids detected in this study have been previously reported either by Cannon et al. (2015), González-Domínguez et al. (2020), or Passa et al. (2023).

Five of the carboxylic acids amounted for 4.10% of blueberry aroma volatiles with butanoic acid detected in all commercial samples (BB1: 262.50±2.04; BB2: 333.81±1.99; BB3: 210.03±1.21) but not identified in the locally-grown Titan AT and Titan ET blueberries. However, only one carboxylic acid namely acetic acid was present in Titan AT whereas no carboxylic acids were found in the Titan ET cultivated at elevated temperature. These results suggest a potential diminishing effect of elevated temperature as a blueberry growing condition which may have inhibited the formation of acids in the Titan ET. Since carboxylic acids are generally described to impart sour, acidic, pungent sensory attributes and none of them were found in Titan ET, these may be the potential reasons of Titan ET (grown at elevated temperature) having significantly less ($P < 0.05$) sour taste (2.63±0.04) than Titan AT (grown at ambient temperature). In summary, elevated temperature conditions may have hindered carboxylic acid formation in Titan ET blueberry which also may have induced less sourness in this sample.

3.4.4. Esters

Esters are major constituents of berry volatiles contributing towards desirable aroma notes like ‘floral’ and ‘fruity’ (Gu et al., 2022; Schwieterman et al., 2014; Ulrich et al., 2018). In this study, the most prominent volatile group in strawberry were esters accounting for 25.23% of strawberry volatile profile and totaling 27 of its members identified in all strawberries. Among these esters, methyl acetate, propyl acetate, ethyl 2-methylbutyrate, and octyl crotonate were identified in all SB1, SB2, and SB3 strawberry samples whose peak areas ranged from 14824.34±4.33–32337.08±2.28, 9617.54±1.84–69649.22±8.14, 2430.39±2.26–3316.65±2.38, and 241.57±0.87–394.67±1.98, respectively. Nine of the esters identified this study namely isopropyl acetate, propyl acetate, butyl acetate, methyl pentanoate, methyl hexanoate, ethyl hexanoate, hexyl isobutyrate, methyl salicylate, and methyl dodecanoate were previously reported by Cannon et al. (2015) in Ciflorette variety. However, only 7 esters were detected by González-Domínguez et al. (2020) in strawberries bred by soilless technique as compared to 27 esters identified in this study – three of which (methyl hexanoate, ethyl hexanoate, trans-hex-2-enyl acetate) were identified in both studies. Passa et al. (2023) detected four esters in Western Greek cultivars, two of which (methyl hexanoate, ethyl hexanoate) were also noted in this investigation.

Similar to strawberries, esters were also detected in the most abundance in all blueberry samples including both the commercial varieties (BB1, BB2, BB3) and local cultivars grown at different temperature conditions (Titan AT, Titan ET), with 16 of its members accounting for 13.11% of total blueberry volatiles. Methyl acetate was detected in all the commercial blueberries

(BB1: 1261.40±4.01, BB2: 1375.29±3.99, BB3: 1186.34±2.19) but was not present in Titan cultivar (Titan AT, Titan ET). BB1 contained higher number of esters such as propyl acetate (71.25±1.83), ethyl hexanoate (920.98±2.92), methyl heptanoate (2276.64±1.88), ethyl cinnamate (89.07±1.01), and methyl dodecanoate (74.22±2.79) that were note detected in any other samples, indicating its rich ester content with desirable sensory descriptors (see Table 3.12) than others. Methyl 2-methylbutanoate having 'apple, chewing gum, fatty, green, lily, powdery, solvent, spirit' sensory descriptors were only observed in BB1 (5360.15±3.04), BB3 (1136.22±1.53), and Titan AT (354.42±0.65) blueberries grown at ambient temperature but were not detected in Titan ET blueberry. In fact, no ester was detected in Titan ET grown at elevated temperature which indicates that temperature variations in growth condition may affect ester formation in blueberries. Previously, Methyl acetate and Ethyl Acetate have been reported by Forney et al. (2022) and Farneti et al. (2017) whereas Ethyl hexanoate has been identified by Farneti et al. (2017) and Qian et al. (2022) in blueberries. That said, thirteen new esters were detected in this study that were not observed in any of these investigations.

3.4.5. Furans

Furans are one of the most important groups of organic compounds in strawberries that impart the typical strawberry aroma and flavor. Making up 5.61% of the strawberry aroma profile in this study, three of the six furans namely 2-butylfuran, 5-methylfurfural, and furaneol (4-hydroxy-2,5-dimethyl-3(2H)-furanone) were detected in all three samples but furaneol had higher intensities than other furans (SB1: 543.52±2.19; SB2: 588.65±2.32; SB3: 512.94±1.74). Furans such as furaneol (4-hydroxy-2,5-dimethyl-3(2H)-furanone) have been widely associated with the characteristic strawberry flavor of ripe strawberries (Porter et al., 2023). Only SB3 contained two furans namely Homofuraneol/ 2-Ethyl-4-hydroxy-5-methyl-3(2H)-furanone (397.07±1.07) and 5-

ethyl-3-hydroxy-4-methyl-2(5H)-furanone (82.12±0.99), although 2-(5H)-furanone was present both in SB2 (320.98±1.63) and SB3 (237.95±1.95). These results indicate SB3 had distinct aroma profile following similar trend as observed in the case of ketones. Furaneol was detected in all three studies of Cannon et al. (2015), González-Domínguez et al. (2020), and Passa et al. (2023) but only Cannon et al. (2015) reported 2-(5H)-furanone and 5-methylfurfural in strawberries which were also identified in this study. However, the current study detected 2-butylfuran, Homofuraneol (2-Ethyl-4-hydroxy-5-methyl-3(2H)-furanone), and 5-ethyl-3-hydroxy-4-methyl-2(5H)-furanone that was not identified in any of these investigations.

In the blueberries, ten furans accounted for 8.20% of the total volatile compounds. 2-(5H)-furanone was detected in all samples (251.88±4.63–1778.17±1.99) except Titan ET. All blueberry samples contained two furans namely 2-methylfuran (170.29±1.38–1707.36±4.67) as well as furaneol/4-hydroxy-2,5-dimethyl-3(2H)-furanone (56.13±1.52–311.90±3.04). Although furaneol is not as important as it is for strawberry hedonic impression, its presence in all blueberries is consistent with the results observed in strawberries in which all samples also contained furaneol. Although two furaneols detected in this study namely furaneol and 2-ethyl furan have been previously reported by Du et al. (2011) and Forney et al. (2022) in southern highbush and wild lowbush varieties, respectively, eight more furans detected in this study have not been identified in these two previously-mentioned investigations.

3.4.6. Ketones

Ten ketones with aromatic derivatives constituted 9.35% of the strawberry volatiles with 3-mercapto-4-methyl-2-pentanone detected in all samples with its peak area ranging from 1467.04±1.52 to 3090.38±1.92. Three of these ketones namely 3-buten-2-one (2569.77±3.53), 3-

heptanone (1015.37±1.31), and 2-tridecanone (86.40±0.95) were only detected in SB2 strawberry, whereas Coumarin and Benzophenone were solely identified in SB1 and SB2, respectively. Cannon et al. (2015) reported the presence of acetoin (3-hydroxy-2-butanone) and 2-tridecanone in French strawberries that were also present in this investigation. Having lower OAVs, ketones are not regarded as key strawberry odorant but some were noted to supplement sweetness by Fan et al. (2021).

Twelve ketones with aromatic derivatives made up 9.84% of volatile in blueberries. Interestingly, 3-mercapto-4-methyl-2-pentanone with 'blackcurrant' aroma was detected only in the local Titan cultivar (Titan AT: 5002.46±6.80, Titan ET: 4547.44±2.88). In addition, 2,3-pentanedione (935.29±1.75) and 3-Hepten-2-one (50.87±0.85) were only identified in Titan ET (grown at elevated temperature), whereas pentan-2-one (1750.47±4.49) and 2-undecanone (88.39±0.99) were only detected in BB1. All these data indicate that the ketone content of the local cultivars was different than the commercial ones. Out of the ten ketones found in this study, Forney et al. (2022) detected 3-heptanone and 2-Undecanone the in highbush variety whereas Farneti et al. (2017) identified 2,3-pentanedione and 2-Undecanone in five commercial cultivars of Italy. In addition, butane-2,3-dione observed in this study was also noted by Qian et al. (2021) in norther highbush varieties of Oregon, USA. In summary, seven new ketones (1-Hydroxy-2-propanone, pentan-2-one, Acetoin, Cyclopentanone, 3-mercapto-4-methyl-2-pentanone, 3-Hepten-2-one, 3-Octanone) were found in this study with their sensory descriptors mentioned in Table 3.12 that were not mentioned by Pico et al. (2022), Forney et al. (2022), Farneti et al. (2017), or Qian et al. (2021).

3.4.7. Lactones

Although five of the lactones were responsible for 4.67% of the strawberry aroma constituency, none of them could not be detected in more than one strawberry. SB2 was detected for both δ-hexalactone (356.36±2.02) and (Z)-Dodec-6-en-4-olide (59.17±0.96). But δ-nonalactone was identified only in SB1 (96.69±1.85) whereas SB3 contained both γ-decalactone (57.11±2.86) and δ-undecalactone (53.71±1.03). γ-decalactone has been reported to drive consumer liking in strawberries by imparting peach-like fruity aroma (Du et al., 2011) which was detected only in SB3, which is indicative of its unique aroma profile. γ-dodecalactone is another important lactone that was not detected in these strawberries but was noticed to enrich strawberry sweetness by Fan et al. (2021).

The four lactones identified in blueberries were γ-Valerolactone, δ-Hexalactone, δ-Decalactone, and γ-Decalactone amounted for 3.28% of blueberry volatiles. Similar to strawberries, γ-Decalactone was noted in BB3 which was grown at ambient temperature. However, BB2 was identified with all the other lactones such as γ-Valerolactone (118.46±2.11), δ-Hexalactone (270.04±1.40), and δ-Decalactone (67.48±1.02) which means that the lactone content of BB2 was better than other samples and was related to likable aroma descriptors such as ‘anise, cocoa, herbaceous, sweet, tobacco, warm, woody’ (sensory descriptors of γ-Valerolactone), ‘Coconut, creamy, fruity’ (sensory descriptors of δ-Hexalactone), ‘fruity, fruity (sweet), peach, sweet’ (sensory descriptors of δ-Decalactone) as given in Table 3.12. No lactones were detected in locally-cultivated Titan AT or Titan ET blueberries. Qian et al. (2021) found γ-Decalactone in ‘Bluecrop’ and ‘Elliot’ (northern highbush varieties) but did not report the other three lactones (γ-Valerolactone, δ-Hexalactone, δ-Decalactone) as identified in this study.

3.4.8. Sulfur and Organosulfur Compounds

Methanethiol and dimethyl sulfoxide were the only two sulfur compounds detected in strawberries, and both were only present in SB3. Previously, Fan et al. (2021b) has reported that methanethiol significantly contributed to green aroma in strawberry descriptive analysis. In this study, SB3 had a very high intensity of methanethiol (82851.84±3.68) with 'earthy, fruity, garlic, garlic (penetrating), leek, onion, rubber, skunk (strong), strong, sulfurous' sensory descriptors associated with it. Dimethyl sulfoxide having 143.57±1.36 peak area is also identified with similar sensory descriptor generally noted as 'alliaceous, fatty, garlic, mushroom, oily, sulfurous'. No organosulfur compounds were detected in the strawberry samples investigated in this study.

Four sulfur compounds and two organosulfur compounds detected in blueberries appeared to play an interesting role in blueberry aroma. Titan ET blueberry grown at elevated temperature contained all four sulfur compounds namely Ethanethiol (1825.24±2.59), 3-methyl-3-sulfanylbutanol-1-ol (762.75±1.56), Dimethyl sulfoxide (924.98±1.05), and Dimethyl disulfide (56.82±0.93) along with Tebuthiuron (129.78±2.27). The presence of dimethyl disulfide has been detected in Canadian highbush varieties by Forney et al. (2022). Usually, sulfurous compounds emit unwanted odors typically describes as cabbage, garlic, or onion (Fan et al., 2021a). These results indicate that sulfur-containing compounds may come to be more prevalent in Titan ET blueberry grown at elevated temperature which may negatively impact its sensory acceptance.

3.4.9. Terpenes and Terpenoids

Flavor predilection in fruits such as strawberry and blueberry is greatly modulated by terpenes and terpenoids (Ferrão et al., 2022). The terpenes and terpenoids combinedly consisted of 6.54% of the total strawberry aroma compounds. When it comes to the terpenes, 1S-()-a-pinene

(1315.63±3.96) and Myrcene (162.18±1.37) were detected only in SB3, whereas SB2 had α-pinene (837.97±2.88) and p-Cymene (3341.20±4.68) present in it. In comparison, SB2 was not identified with any terpenes. Two of these terpenes (α-pinene and p-Cymene) were also detected by Cannon et al. (2015) in French strawberries. Among these three terpenoids, methyl eugenol was only detected in SB2 (90.60±1.02). However, Citronellal was present in SB1 (120.59±2.46) and SB2 (291.79±1.28), whereas α-Terpineol was detected in SB1 (308.78±1.66) and SB3 (236.64±1.50). Both of these terpenoids (citronellal and α-terpineol) have been previously reported by Cannon et al. (2015). That said, linalool – a terpenoid with an enhancing effect on strawberry flavor (Schwieterman et al., 2014) – was not found in any of the strawberries investigated in this study.

In blueberries, the terpenes and terpenoids contributed towards 7.38% of overall volatile profile, respectively. No terpenes were detected in Titan AT sample whereas Titan ET contained α-Phellandrene (308.66±1.66) and D-Limonene (861.22±1.84). All of these terpenes were also reported by Pico et al. (2022) in northern highbush cultivars. Among the terpenoids, camphor was present in all samples at 85.52±0.93–464.84±2.57 peak area intensity except Titan AT. Linalool, one of the important terpenoids in berries, was detected in BB1 (270.69±2.77), BB3 (56.67±1.26), and Titan AT (886.92±1.72). The presence of Citronellol and Eugenol was noted only in BB2 with 185.93±0.94 and 53.85±0.92 peak area intensities, respectively. (Z)-Citral/neral and methyl eugenol was only detected in commercial blueberries with BB1 and BB3 containing 70.21±0.81 and 87.66±1.69 peak area intensities of these terpenoids, respectively. Pico et al. (2022) and Qian et al. (2022) detected four out of six of these terpenoids such as linalool, citronellol, (Z)-citral/neral, and eugenol in northern highbush blueberries cultivated in North America. However, two of these terpenoids detected in this study namely camphor with ‘aromatic, camphor, dry, fragrant, green, leafy’ sensory descriptors and methyl eugenol having ‘carnation, cinnamon, clove, fresh, mild, spicy, sweet, warm’ aroma notes were not reported by the previously-mentioned research groups. Ferrão et al. (2022) reported eight terpenes that also included linalool, β-myrcene, and D-limonene as identified in this study to be key drivers of consumer aroma preference with enormous potential in targeted blueberry breeding.

3.4.10. Other Volatile Compounds

Hydrocarbons and its aromatic derivatives accounted for 6.54% and 11.48% of the strawberry and blueberry volatile compounds, respectively. In addition, one amine (trimethylamine), one organochlorine compound (trichloroethane), two phenols (2-methyl phenol, 4-vinylguaiacol), one phenolic compound (rheosmin), one pyrrole (pyrrole), six pyrazines (2-ethyl-3-methylpyrazine, 2-ethyl-3,6-dimethylpyrazine, 2-ethyl-3,5-dimethylpyrazine, 2-isopropyl-3-methoxypyrazine, 2,3-diethyl-5-methylpyrazine, 2-isobutyl-3-methoxypyrazine), and one pyridine (2-pentyl-pyridine) were detected in strawberries. The blueberry samples also contained two amines (trimethylamine, aniline), two organochlorine compounds (Trichloroethane, Cyclohexanecarbamic acid, - N-ethylthio, - S-ethyl ester), one phenol (phenol), one phenolic compound (rheosmin), one pyrazine (pyrazine), two organosulfur compounds (2-methylthiophene, tebuthiuron), and one thiazole (2-acetylthiazole). These volatiles may have formed as intermediary compounds during e-nose incubation and no previous studies have reported any these compounds to impart aroma or flavor in strawberries or blueberries to the best of our knowledge.

3.5. Correlation between Strawberry Furaneol Content and Descriptive Aroma Liking Scores

Furaneol (4-Hydroxy-2,5-dimethyl-3-furanone) is one of the key contributors of ripe strawberry aroma with a significant role in strawberry flavor development during ripening stages (Fan et al., 2021a; Ubeda et al., 2012). Figure 3.9 illustrates the change of furaneol content in different strawberry samples for 5 days.

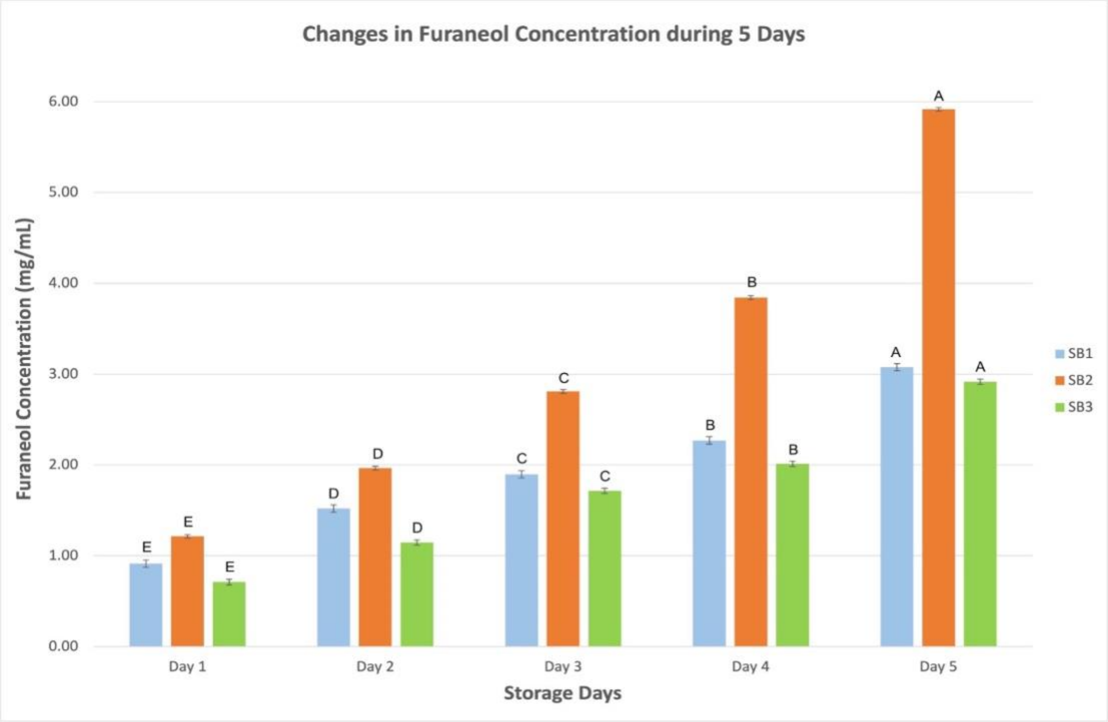


Figure 3.9. Changes in furaneol content (mg/mL) in SB1, SB2, and SB3 strawberries during 5 days' storage period; Days containing different letters have significantly different (*P* < 0.05) furaneol concentration (mg/mL) for each strawberry sample.

As shown in Figure 3.9, furaneol content (mg/mL) in strawberries increased throughout their storage from Day 1 to Day 5. The furaneol content in SB1 at Day 1 to was found to be 0.91±0.04 mg/mL and increased up to 3.08±0.06 mg/mL at the end of storage (Day 5). In contrast, SB2 contained significantly higher (*P* < 0.05) furaneol content throughout the entire shelf-life within the range of 1.21±0.01–5.92±0.01 mg/mL, whereas relatively lower concentration (significant at $P < 0.05$) was observed in SB3 (Day 1: 0.71±0.01 mg/mL; Day 5: 2.92±0.0 mg/mL) among all three samples. Similar observations were made by Lavid et al. (2002) who also reported a sharp increase of furaneol during strawberry ripening stages.

Table 3.13. Pearson's correlation coefficients (*r*) indicating relationship between descriptive aroma attributes and furaneol content (mg/mL) of SB1, SB2, and SB3 strawberry samples.

Attributes	Fruity	Floral	Sweet	Green	Pungent	Overripe	Overall	Furaneol content
Fruity	$r = 1$ $P = 0$							
Floral	$r = -0.093$ $P = 0.742$	$r = 1$ $P = 0$						
Sweet	$r = 0.925$ $P < 0.0001$***	$r = 0.095$ $P = 0.737$	$r = 1$ $P = 0$					
Green	$r = -0.678$ $P = 0.006$**	$r = 0.509$ $P = 0.053$	$r = -0.644$ $P = 0.010$*	$r = 1$ $P = 0$				
Pungent	$r = -0.911$ $P < 0.0001$***	$r = 0.320$ $P = 0.244$	$r = -0.808$ $P < 0.0001$***	$r = 0.829$ $P < 0.0001$***	$r = 1$ $P = 0$			
Overripe	$r = 0.230$ $P = 0.410$	$r = -0.756$ $P = 0.001$**	$r = 0.134$ $P = 0.634$	$r = -0.784$ $P = 0.001$**	$r = -0.526$ $P = 0.044$*	$r = 1$ $P = 0$		
Overall	$r = 0.900$ $P < 0.0001$***	$r = 0.023$ $P = 0.935$	$r = 0.952$ $P < 0.0001$***	$r = -0.693$ $P = 0.004$**	$r = -0.850$ $P < 0.0001$***	$r = 0.199$ $P = 0.476$	$r = 1$ $P = 0$	
Furaneol content	$r = 0.467$ $P = 0.079$	$r = -0.651$ $P = 0.009$**	$r = 0.431$ $P = 0.109$	$r = -0.864$ $P < 0.0001$***	$r = -0.704$ $P = 0.003$**	$r = 0.806$ $P < 0.0001$***	$r = 0.488$ $P = 0.065$	$r = 1$ $P = 0$

* means $P < 0.05$; ** means $P < 0.01$; *** means $P < 0.001$.

The furaneol content (mg/mL) in SB1, SB2, and SB3 strawberry samples was correlated with descriptive aroma liking scores of the trained panel and the Pearson's correlation coefficients (r) denoting the strength of their association is given in Table 3.13. As mentioned in Table 3.13, a very strong positive association ($r = 0.806$; $P < 0.0001$) was observed between the furaneol content (mg/mL) and the overripe aroma rated by the descriptive panel on a 15-cm line scale. It means that the trained panels' overripe aroma liking scores of strawberries tend to increase with an increase in furaneol content (mg/mL). This result also suggest that the overripe strawberry aroma may be modulated by the furaneol concentration present in it, which is consistent with the fact that furaneol tends to increase drastically in the later stages on ripening to impart unique flavor in ripe strawberries (Pérez et al., 1996). In addition, the strawberry furaneol content (mg/mL) was negatively correlated with green ($r = –0.864$; $P = 0.0001$), pungent ($r = –0.704$; $P = 0.003$), and floral ($r = –0.651$; $P = 0.009$) aroma liking of expert panelists. These findings indicate a decline in expert panel's ratings for pungent, green, and floral aroma with an increase in furaneol concentration (mg/mL) throughout the storage. Also, these results are in line with the data from descriptive analysis in which the expert panels ratings on green, pungent, and floral decreased during the 5 days of shelf-life. To sum up, the aroma liking for green, pungent, and floral attributes will lessen but overripe aroma will intensify as days pass by in their post-harvest period. Considering these findings, it is plausible to deduce that strawberry furaneol may be a potential indicator of its overripe aroma. In a similar effort to comprehend how volatile composition impacts the hedonic perception of strawberry, Schwieterman et al. (2014) reported a positive correlation between furaneol and strawberry flavor intensity. Loehndorf et al. (2000) also found that strawberry flavor along with sweetness were highly correlated ($r = 0.90$) to strawberry furanone content. In regard to the above-mentioned findings, furaneol in strawberries should be regarded as an important factor for targeted breeding due to their immense impact in strawberry sensory likability (Porter et al., 2023).

4. Conclusion

The sensory acceptance of strawberries and blueberries was investigated in this study during a shelf-life of five days. Based on descriptive analysis, the flavor and overall aroma acceptance of the commercial strawberries and blueberries remained satisfactory after they have been bought from the stores and stored at cold condition (~4°C) for 5 days. The e-nose and e-tongue exhibited satisfactory discrimination potential to detect changes in volatile and non-volatile sensory profiles of strawberry and blueberries throughout this shelf-life duration. In addition, the instrumental analyses of the e-nose and e-tongue showed satisfactory correlation to descriptive aroma and taste intensities of the expert panel, which means that these sensory instruments have the predictive potential to project the descriptive sensory scores of strawberries and blueberries as per their corresponding instrumental measurements. Subsequently, a positive correlation was found between the strawberry furaneol content and overripe aroma whereas floral, green, and pungent aromas were negatively associated with the concentration of furaneol. The effect of elevated temperature as the blueberry growing condition may have contributed towards relatively ‘less sour’ fruits with no carboxylic acid and ester formation as compared to those of the same Titan cultivar cultivated at ambient temperature. Moreover, the e-nose volatile analysis revealed that sulfur containing compounds were prevalent in elevated temperature blueberries compared to those grown at ambient temperature which may impart off-putting odor notes such as ‘cabbage, garlic or onion’ to potentially downgrade the sensory acceptability of these berries. Further research is needed to confirm how elevated temperature may impact the sensory qualities of blueberries with more cultivars subjected to temperature variations in their growing conditions.

In summary, this study demonstrated superior sensitivity of e-nose and e-tongue as compared to the descriptive human panel with their very high discrimination index despite no significant difference in the expert panels' evaluation of some descriptive attributes. Findings of this study may be beneficial for reducing the associated costs of descriptive analysis to be substituted and/or supplemented by the electronic senses like e-nose and e-tongue in breeding advanced selections of berry fruits with optimized sensory profiles.

5. Limitations

The storage time for sample evaluation could not be controlled for the commercially purchased strawberries (SB1, SB2, SB3) and blueberries (BB1, BB2, BB3) since they were collected from the supermarket and the information on how long these fruits were kept in the store shelves was not made available to the researchers. Hence, the sensory attributes of these strawberries and blueberries reported in this investigation may seem different depending on their storage in stores at the time of sensory evaluation.

6. Legal Disclaimer

The authors neither endorse any specific strawberry or blueberry brand over another nor do they make any claim about the quality of brands investigated in this research. These strawberries and blueberries have been used for research purposes only. Sensory perception may vary from one trained panel to another. The results of sensory evaluation reported in this study, by any means, must not be construed as an absolute measure of sensory qualities for strawberries and blueberries.

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Conclusion

The first study characterized the sensory profiles of different stevia blends and confirmed the potential of e-tongue to discriminate stevia solutions with different Reb A, Reb D, and Reb M concentrations. The consumer evaluation of ice cream prepared with these stevia blends was acceptable, but the stevia-sweetened carbonated beverage was not liked by the panelists. The descriptive analysis of stevia blends and consumer liking scores of these stevia-sweetened food products was well-correlated, indicating that consumer liking scores could be predicted by the descriptive panel data. The second study investigated the correlation between electronic senses and descriptive analysis of strawberries and blueberries over 5 days of storage. High discrimination indices were observed both in the e-nose and e-tongue for their superior discrimination capability to detect volatile and non-volatile changes in these fruits. Also, the measurements of e-nose and e-tongue had a satisfactory correlation with descriptive analysis data showing their good predictive ability to estimate expert panels' ratings. The volatile aroma constituents of strawberries and blueberries comprised 107 and 122 compounds, respectively. Esters, alcohols, aldehydes, furans, ketones, lactones, terpenes, and terpenoids were the major components in both strawberry and blueberry volatile aroma profiles. Lastly, the descriptive panel's ratings on overripe aroma were positively correlated to strawberry furaneol content while sensory scores of green, pungent, and floral aroma had a negative relationship with furaneol concentration. Locally-cultivated blueberries grown at an elevated temperature had less sourness with no presence of carboxylic acid or ester but contained high sulfur-containing compounds that might affect their aroma likability, revealing a potential negative impact of elevated temperature in the blueberry growing condition in blueberry aroma acceptance.