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Aroma Comparison between Plant-based Hamburgers and Traditional Beef Hamburgers

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Abstract

The aim of the study was to investigate the differences in aroma in the many plant-based hamburger analogues in the market today when compared with traditional beef hamburger. For that purpose, we investigated the aroma components using headspace gas chromatography-olfactometry and gas chromatography coupled to mass spectrometry analytical methods. The lipid-derived aldehydes and Maillard reaction compounds were key contributors to the characteristic aroma of a beef hamburger. And that most of the plant-based burgers in the market today were unable to replicate that profile. The plant-based meat analogues displayed a more roasted odor character with higher pyrazine levels and then many show evidence to the addition of other flavor compounds and spices to give the perception of a flavored meat analogue. These approaches resulted in higher flavor intensity; however, the result was something very sensorially different than the sweet, juicy, buttery, and meaty character of beef hamburger. Based on these findings, replication of the characteristic aroma of beef hamburger is complex. This work provides new insights into the key aroma contributors of beef hamburgers and the challenges that exist in trying to replicate it with plant-based meat analogues.

Keywords: hamburger aroma, beef aroma, flavor, plant-based hamburgers, gas chromatography – olfactometry (GC-O), solid phase micro extraction (SPME), gas chromatography – mass spectrometry (GC-MS), principal component analysis (PCA), hierarchical cluster analysis (HCA)

1. Introduction

The aroma of cooked meats plays a significant role in consumer enjoyment and preference of these food products. The flavor of beef is composed of umami and juicy mouthfeel to the savory, sweet, fatty, and roasted-meaty aroma that we smell during the cooking process (Brewer et al., 2006; Wang et al., 2022, Yamada et al., 2020). Raw meat has very little aroma character except for some bloody, metallic notes. It is during the cooking process that aroma is generated through the characteristic Maillard reactions, and lipid oxidation to generate volatile lipid aldehydes (Wang et al., 2017). The degree of Maillard reactions achieved in the cooking process is dependent of the amount of moisture present and the temperature. Under high moisture environments, lipid aldehydes and some essential meaty notes are developed. However, as water is removed from the system the Maillard reactions are accelerated and yield more diverse pyrazines, complex sulfur molecules, caramelized sugar compounds and brown polymers (Ruan et al, 2015). The raw meat may have limited odor; however, it provides the key ingredients such as amino acids and sugars that drive the development of meaty flavor characteristics. In addition, the fatty acid profile leads to different ratios of volatile fatty aldehydes which are said to give specificity to the meat flavor (Schumacher et al., 2022; Yang et al., 2022).

Recent awareness to the impact of animal farming on climate change (Schiermeier et al., 2019) and the need to feed a growing population has accelerated experimentation into alternative proteins in our food supply chain. Plant-based protein products have become a central focus in new product launches. This is very apparent in the development of plant-based hamburger options in the market today. Soy and pea protein are the leading substitutes for these meat analogues today (Malek et al., 2023; Ge et al., 2022). These proteins have been processed in extruders and can yield much better texture attributes than past attempts. In addition, mixtures of oils are now able to provide a similar melt and juiciness to the burger. However, one area that still presents a challenge is to develop a plant-based meat analogue with the same aroma perception of the animal protein. Some approaches are to add a meat flavor to the analogue or to add the meat flavor precursors to so that aroma is formed during the cooking process. The ability to replicate the exact precursor combination is a challenging task as some ingredients may not be available and the question of whether we know exactly what precursors are needed to achieve the meat specific flavor outcome.

Therefore, the aim of this study was to perform an evaluation of the aroma and volatile differences between a beef hamburger and various plant-based hamburgers in the market today. A detailed study like this doesn't exist in the literature today but most likely resides within the competitive knowledge of larger private organizations. This study provides a forum for discussions that could help drive further improvements in the taste and aroma development of alternative protein meat analogues.

2. Materials and Methods

2.1 Chemicals

Methanethiol, dimethyl sulfide, trimethylamine, 2-methylpropanal, 3-methylbutanal, 2,3-butanedione, 3-hydroxy-2-butanone (acetoin), gamma-octalactone, isovaleric acid, 2-methyl-3-furanthiol, hexanal, heptanal, octanal, nonanal, (E)-2-nonenal, (Z)-2-nonenal, (E,E)-2,4-nonadienal, (E,Z)-2,4-decadienal, (E,E)-2,4-decadienal, indole, 1-octen-3-ol, 1-octen-3-one, dimethyl trisulfide, phenylacetaldehyde, p-cresol, guaiacol, 2-acetyl-2-thiazoline, 4-hydroxy-2,5-dimethyl-3(2H)-furanone (furaneol), methional, acetic acid, butyric acid, hexanoic acid, octanoic acid, decanoic acid, , ammonium sulfate, and alkane standard (C7-C30) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ultra-pure water was sourced from a Milli-Q system (Millipore, Bedford, MA, USA).

2.2 Sample Preparation – Cooking of Hamburgers and Plant-based Hamburgers

Beef hamburgers patties, 80% lean: 20% fat (80:20), were obtained from a local Kroger grocery store in Fort Mitchell, KY. Plant-based hamburgers: Beyond meat, Impossible Foods, Incogmeato®, and Simply Truth™ Emerge were obtained from local grocery stores (Kroger, Hy-Vee, Meijer). Patties were cooked on a flat-griddle at 325 ℉ for 5 min on each side, flipped once, and to a final internal temperature of 140-150 ℉. Immediately after cooking, the patties were minced and 2 g of sample was placed in 22-ml SPME vials for analysis by SPME-GC-MS-O and sensory profiling.

2.3 SPME Fiber and Extraction Conditions for Hamburger Samples

The 3-phase SPME fiber, 2cm DVB/CAR/PDMS (Supelco, Bellefonte, PA, USA) was chosen for the headspace extraction of hamburger volatiles as this fiber has been shown to extract the widest polarity of volatiles and for its proven capability of extracting flavor molecules (Al-Taher & Nemzer, 2020; Zhang et al., 2021). A sample from each hamburger patty were weighed in triplicates for analysis. For SPME analysis 2.0 +/- .05 g sample was placed in a clear 20ml screw-cap vial with PTFE septa (Pal Parts, Raleigh, NC). The extractions were performed using a Gerstel MPS SPME autosampler (Gerstel, Linthicum, MD, USA). An equilibration time of 10 min was followed by 20 min at 50 ℃, using the heating agitator. Then, the fiber was desorbed into an Agilent split/splitless GC inlet operated 250 ℃ in splitless mode for 6 min.

2.4 Gas Chromatography-Mass Spectrometry (GC-MS)

The analysis of aroma volatiles extracted by HS-SPME, and liquid injection was performed using a Model 7820A gas chromatograph (GC) equipped with a 5977 mass spectrometer detector (MSD) and Flame Ionization Detector (FID) from Agilent (Agilent Technologies, Santa Clara, CA, USA). Olfactometry was performed using the Gerstel Olfactory Detection Port (ODP 3) which was connected to the Agilent 7820a gas chromatograph (GC) with the Agilent 5977 mass spectrometer (MS). The spilt ratio was 2:1 (olfactory port : MS) using the Gerstel UFlowManager®. The GC was coupled with a Gerstel Multipurpose Sampler (MPS) with SPME capability (Linthicum, MD, USA). The injector port had a 0.754 mm deactivated GC liner, and the inlet was kept at a constant temperature of 250 ℃. A fused silica HP-5ms-UI column (30 m x 0.25 mm ID x 0.25 μm thick film) Agilent Technologies (Santa Clara, CA, USA) was used for analysis. Helium was the carrier gas with a constant flow rate of 1 mL/min. The initial oven temperature was 50 ℃ with a hold time of 1 min. Then the temperature rose to 240 ℃ at 15 ℃/min then held for 5 min. The MSD operated in electron ionization mode at 70 ev. The MSD transfer line was set at 280 ℃. The ion source was heated at 230 ℃ and the MS quads were heated at 150 ℃. SPME was performed without solvent delay. The mass acquisition range was 35 to 250 m/z.

2.5 Sensory Aroma Comparison of the Cooked Beef and Plant-Based Hamburgers

Freshly cooked beef and plant-based hamburgers were macerated with a fork and 25 g portions were placed in 50-ml glass beakers with watch glass covers. The samples were presented with a beef hamburger reference sample for comparison to the 5 judged samples (4 plant-based hamburgers and 1 beef hamburger). The panelists were asked to judge the aroma only, and on a degree of difference scale: 0 = no difference; 1 = similar aroma profile, could be described as beef hamburger aroma, only slightly different; 2 = difference can easily be recognized, yet it shows a resemblance to hamburger aroma; 3 = very different aroma profile, not recognizable as beef hamburger. In addition, the panel was asked to provide aroma descriptions for the 5 samples. There were 7 panelists, experienced in aroma analysis and who regularly consume beef hamburgers. The degree of difference score was averaged to report a final score and aroma descriptions were compiled into one table.

2.6 Olfactometry

Each hamburger sample was evaluated by three olfactory panelists who were trained in GC-O and odor recognition; each performed 2 replications. Intensity of odor compounds was rated on a 9-point scale (low, medium, strong; – and +). For example, medium can be medium -, medium, or medium +. An aroma peak was determined to be aroma active if it was detected with at least half of the analyses.

2.7 Compound Identification

Compound identifications was determined by a combination of retention indexes, mass spectra comparison with libraries (NIST 14, FFNSC3), odor description, and confirmation by injecting authentic standards on the same columns. Alkane linear retention indexes were obtained using a (C_7-C_{30}) alkane standard mixture. Linear retention indexes of aroma compounds were calculated on the DB-5 GC columns. The identification of 2-acetyl-1-pyrroline was based on retention index, odor, extracted ions for the compound, and running of a reference sample of cooked jasmine rice which is known to be high in this compound (Guo et al., 2020)

2.8 Data Analysis

Aroma volatile compound identification and peak area calculation were performed using Agilent Technologies' ChemStation software (version F.01.03). Microsoft Excel 2016 (Redmond, WA, USA) was used for creation of bar charts. JMP and XLSTAT were used for data processing, principal component analysis (PCA) and hierarchical cluster analysis (HCA).

3. Results

3.1 Aroma-active Compounds in Hamburger

Initial evaluation of hamburger was by SPME-GC-MS-O as this approach has been demonstrated to provide valuable insights into the aroma of various cooked beef products (Zanget al., 2020). Table 1 lists the odor active compounds we identified in grilled beef hamburger. From this list of 33 odor active compounds detected by the GC-O panelists, we were able to identified 30 (3 listed as unknown identity). In this analysis, many volatiles were identified such as lipid-derived aldehydes (hexanal, octanal, nonanal), sulfur compounds (methanethiol, dimethyl sulfide, dimethyl trisulfide, 2-methyl-furanthiol), buttery compounds (acetoin, diacetyl), roasted compounds (2-acetyl-1-pyrroline, 2-acetyl-2-thiazoline), stinky acids (3-methyl butyric acid) and caramelized, sweet compounds (furaneol, 2-methyl propanal, 3-methyl propanal). The characteristic hamburger aroma is not derived from one single compound but by a mixture of sweet, roasted, fatty, buttery, sulfury, and sweaty compounds together and at the right ratio. However, some of these compounds may play a stronger role.

Table 1. List of Important Aroma Active Compounds Identified in SPME-GC-MS-O of the 80:20 Hamburger

Table 1 Aroma important compounds identified in SPME-GC-MS-O of Beef Hamburger				
Time (min)	Odor Description	Odor Intensity	Compound Identity	Retention Index (DB-5)
2.18	decay, dead fish	L	Methanethiol	<600
2.26	sulfury, cabbage	M	Dimethyl sulfide	<600
2.31	amine stinky note	M	trimethylamine	<600
2.58	malty, buttery	L	2-methyl propanal	<600
2.65	sulfur note	L	unknown 1	<600
2.69	buttery	S	diacetyl	600
2.76	stinky note	L	unknown 2	612
3.04	malty, cocoa	M	3-methyl butanal	640
3.30	buttery	L	acetoin	722
4.21	malodor acid stinky	M	butyric acid	790
4.26	green	M	hexanal	802
4.70	sweaty	M	isovaleric acid	854
5.06	roasted, nice, yeasty	M	2-methyl-3-furanthiol	862
5.34	green, algae, yucky	M+	heptanal/cis-4-heptenal	902
5.40	potato	S	methional	909
5.61	roasted, nice, nutty	M	2-acetyl-1-pyrroline	925
6.15	earthy	L	1-octen-3-ol	978
6.20	mushroom, earthy, dirt	M	1-ocetn-3-one	981
6.26	stinky, harsh	M	Dimethyl trisulfide	976
6.48	citrus, orange	M+	octanal	1001
7.02	floral, sharp	L+	phenylacetaldehyde	1046
7.08	caramelized sugar note	M+	furaneol	1058
7.27	stinky, barny	L	p-cresol	1075
7.38	earthy L	L+	guaiacol	1085
7.48	fatty aldehyde, floral, waxy	M	nonanal	1104
7.63	nice, roasted, meaty, popcorn	M+	2-acetyl-2-thiazoline	1110
8.00	plastic vinyl	M	(E)-2-nonenal	1154
8.09	plastic vinyl, cardboard	M	(Z)-2-nonenal	1162
8.14	fatty aldehyde, waxy	M	2,4-nonadienal	1217
8.82	caramelized sugar note	L	unknown 3	1248
9.65	fried, fatty aldehyde	L+	(E,Z)-2,4-decadienal	1280
9.80	stinky , mothballs	L+	Indole	1290
9.91	fried, fatty aldehyde	M	(E,E)-2,4-decadienal	1310

During the GC-O analysis, we record the intensity of the odorant detected at the sniff port. Diacetyl and methional were rated as strong odor character, followed by heptanal, octanal, furaneol, and 2-acetyl-2-thiazoline (rated M+). Fifteen other compounds were rated as medium (M) intensity. In our experience, the strong and medium rated odorants are considered to be key drivers to the aroma of the food product, with the low intensity rated odorants playing a supporting role.

3.2 Sensory Aroma Comparison of the Plant-based Hamburger to Beef Hamburger

The 5 hamburger samples (1 beef and 4 plant-based) were evaluated sensorially by a 7-member panel trained in difference testing. The panel was presented with samples of the 5 hamburger samples and asked 2 questions: (1) How similar is it to the control beef hamburger; and (2) Use your own descriptors to describe the aroma of the samples, including the beef hamburger. These results are summarized in Table 2. The beef hamburger was described as buttery, fatty, with meaty and chargrilled notes. Of the 4 plant-based prototypes, only one product seemed to target the authentic hamburger aroma (Brand A) and it displayed a simply fatty, buttery, grilled aroma similar to a reheated hamburger. The other 3 plant-based hamburgers all exited stronger aroma characters such as yeasty, meaty, roasted, and one even having stronger onion, garlic, and barbeque sauce odors.

3.3 Principal Component Analysis

Principal component analysis (PCA) was performed on the volatile data to investigate how these products group relative to the beef hamburger (Figure 1). This plot of PC1 vs PC2 represents 62.9% of the variance in the volatiles compounds profile. The loadings plot shows the compounds responsible for the variance and grouping seen in the scores plot. The PCA data shows the triplicate analysis of each sample plus a mean average data point. The beef hamburger is position in the bottom left corner and plant-based burger Brand A is closest. This observation is consistent with the sensory panel data which gave Brand A the lowest degree of difference score. The loadings plot show that lipid aldehydes are closely associated in the direction of the beef hamburger while Brands B, C, and D are positioned further away and the data suggest that sulfur and sugar degradation compounds are driving that differentiation.

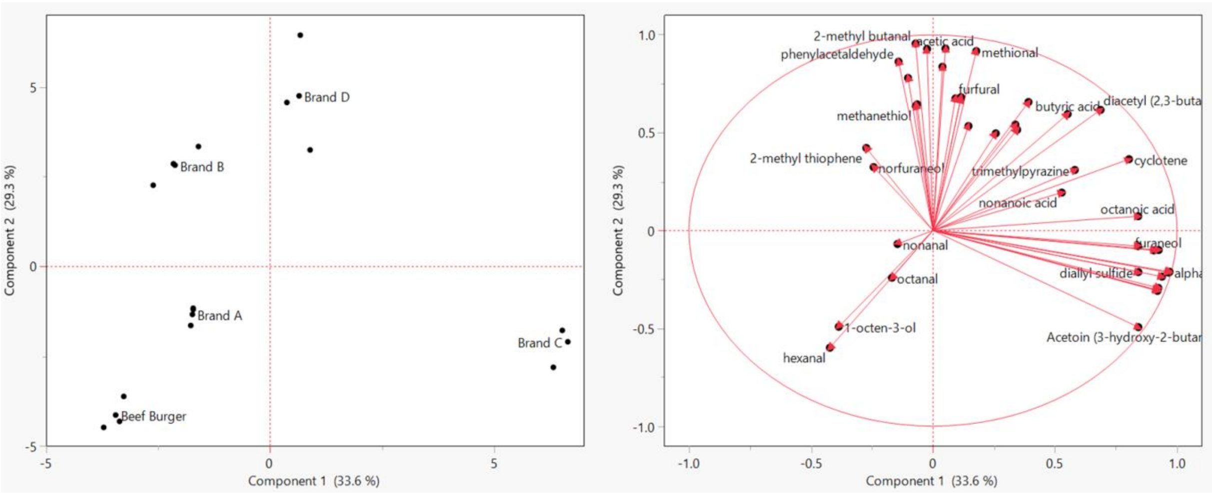

Figure 1. Principal Component Analysis (PC1 vs. PC2) of the Volatile Data in the Beef and Plant-based Hamburger Samples

3.4 Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) was employed to further evaluate the data and highlight synergies that might be apparent from a heat map. Figure 2 shows the two-way clustering analysis of the volatile data from the five hamburger samples. The HCA analysis correlates to the PCA data as Brand A is clustered with beef hamburger. The heat map shows elevation of the lipid aldehyde molecules and low levels of the other compounds. Conversely, Brands B, C, and D have very distinct heat map profiles and are driving by higher levels of roasted, meaty, and caramelized sugar aroma compounds which correlate to the sensory panel data in Table 2.

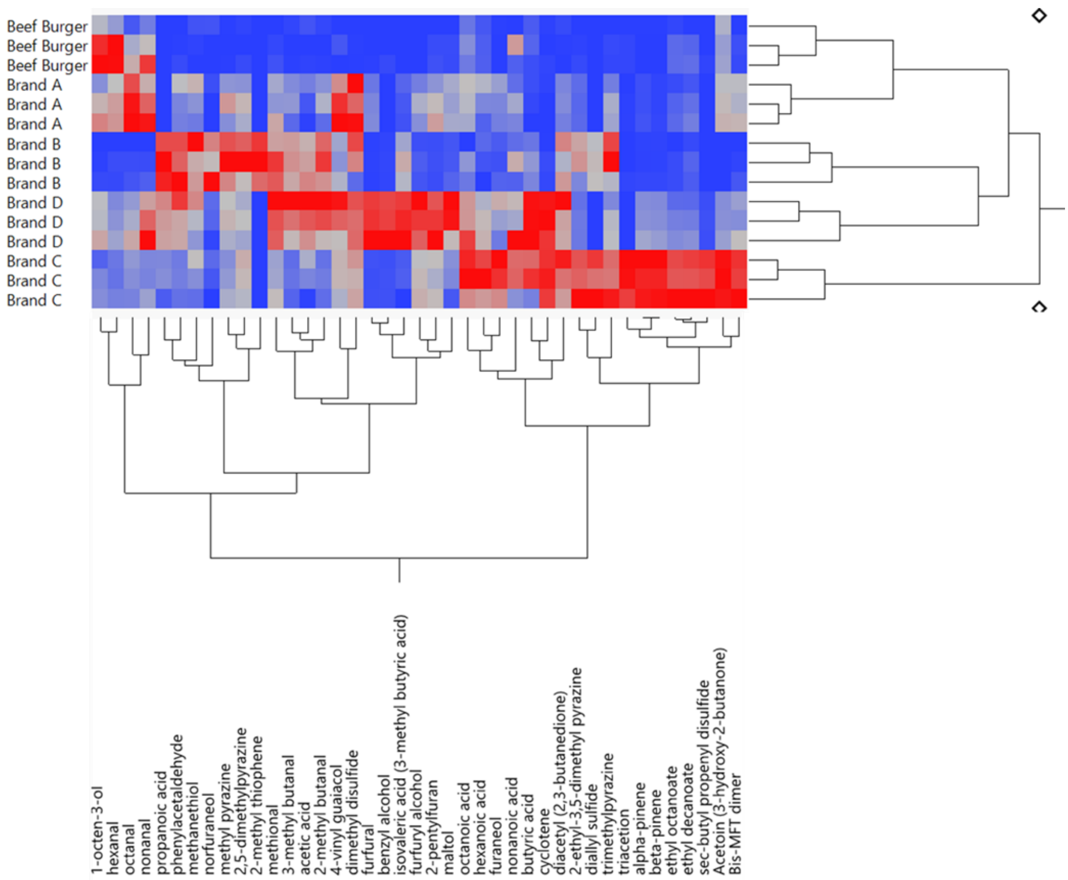

Figure 2. Hierarchical Cluster Analysis of the Volatile Data in the Five Hamburger Samples

A bar chart focused on the fatty aroma compounds, lipid aldehydes, is shown in Figure 3. In this chart the beef burger is highest in lipid aldehydes, especially hexanal, compared to the plant-based burgers. However, Brand A has a similar profile to the beef hamburger. Next, we plotted the roasted, nutty, earthy pyrazine compounds as shown in Figure 4. This Figure shows the significant difference in pyrazine compounds between a beef hamburger where pyrazines are low and the plant-based pyrazines where they are significantly higher which would lead to a more roasted, earthy, nutty aroma perception. In the sensory panel, Brand D was described as sweet and barbeque sauce like. The level of caramelized sugar compounds are very high in this product as shown in Figure 5 were maltol, cyclotene, and furaneol are displayed in the chart. These compounds would give are strong sweet aroma character.

Table 2. Sensory Aroma Profile of the Plant-based Products to Beef Hamburger

Product	Sensory Descriptors	Degree of Difference*
Beef Hamburger	sweat, fatty, buttery, meaty, savory, characteristic hamburger aroma, backyard grilled hamburger	0.0
Brand A	meaty, fatty notes, like reheated hamburger, not fresh but like frozen and reheated hamburger	1.6
Brand B	yeasty, grainy, corn chips aroma, meaty, can cat food aroma, tuna fish odor	2.1
Brand C	sulfury, garlic, onion, strong unpleasant aroma, vegetable soup aroma	2.7
Brand D	very sweet aroma, barbeque sauce like aroma, acetic spicy, tangy spice aroma	3.0

*0 = no difference

1 - similar aroma profile, could be described as beef hamburger aroma, only slightly different

2 - can easily recognized as different aroma from beef hamburger control, but with resemblance of hamburger aroma

3 - very different aroma profile, not recognizable as beef hamburger

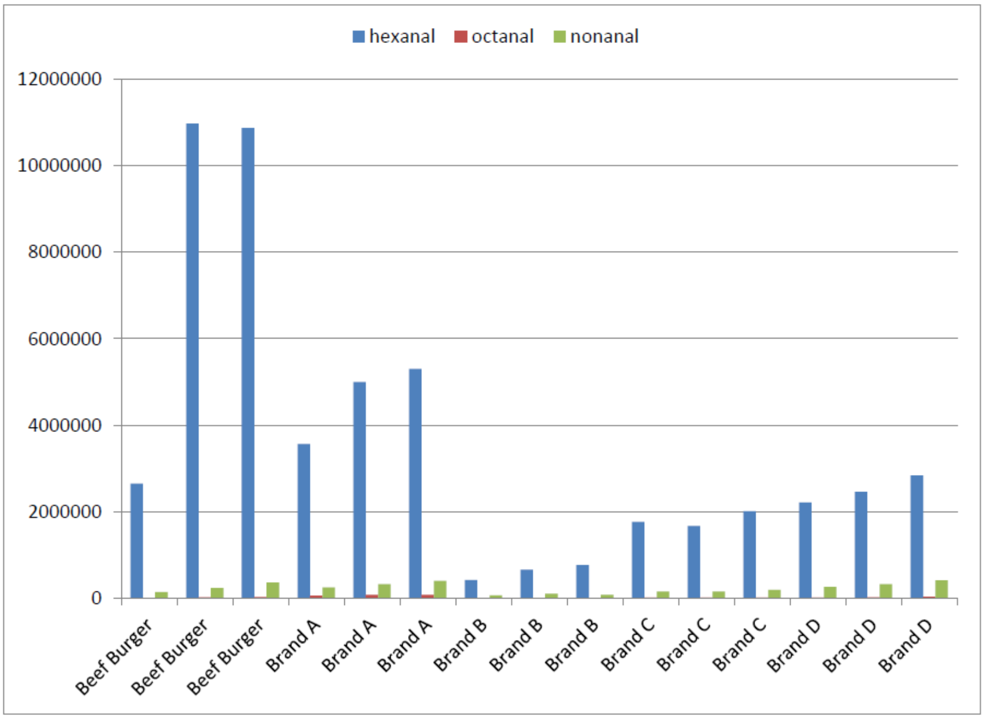

Figure 3. Relative Fatty Lipid Aldehyde Compound Differences between Beef Hamburger and Plant-based Hamburgers

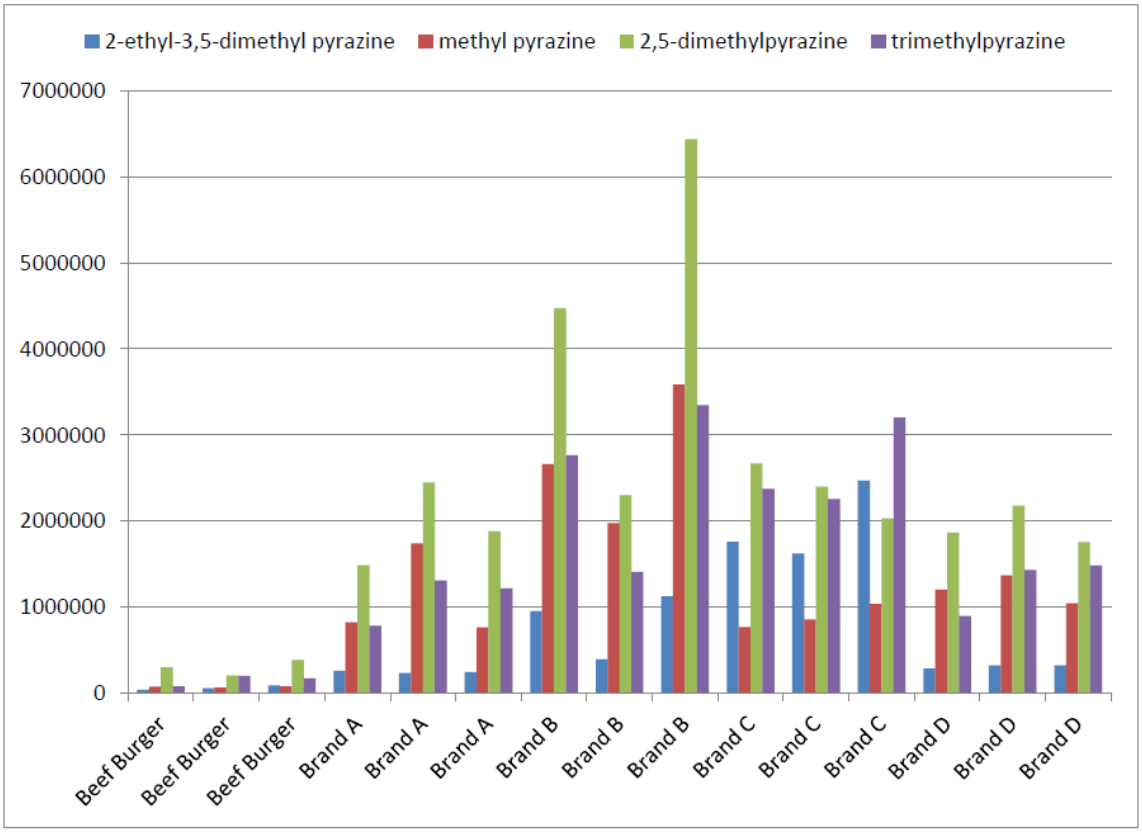

Figure 4. Relative Pyrazine Compound Differences between Beef Hamburger and Plant-based Hamburgers

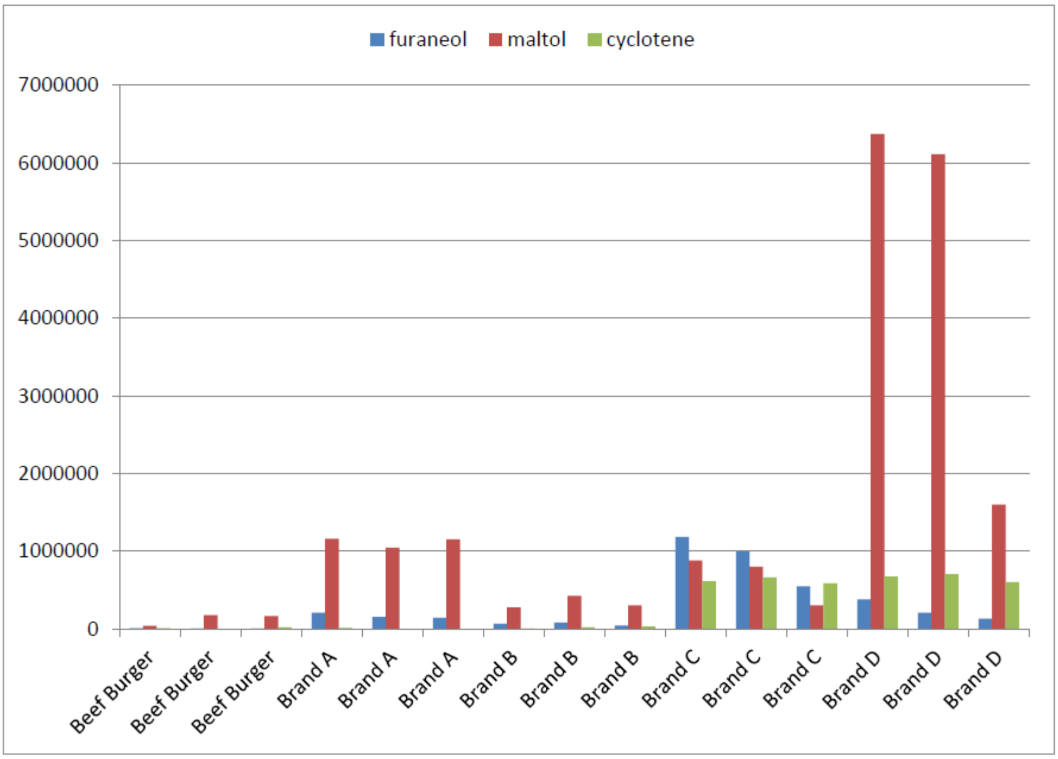

Figure 5. Caramelized Sugar Aroma Compound Differences between Plant-based Hamburgers Compared to Control (80:20 hamburger)

Another attribute that was picked up by the sensory panel was the presence of sulfury, garlic and onion aroma character in some samples. Figure 6 shows the levels of 2-methyl thiophene, diallyl sulfide (garlic), and sec-butyl propenyl disulfide (garlic) for the samples. The addition of these compounds is driving significantly the sulfur and spice character perceived by the sensory panel for Brands B, C, and D. The final comparison we made was between the levels of Strecker aldehydes in the samples (Figure 7). Strecker aldehydes are formed from the breakdown of amino acids by decarboxylation and deamination which produces a volatile aldehyde compound. Many of the Strecker aldehydes are strong aroma compounds, such as: methional, phenylacetaldehyde, 3-methylbutanal, and 2-methylpropanal. These compounds are much higher in the plant-based products compared to the beef hamburger.

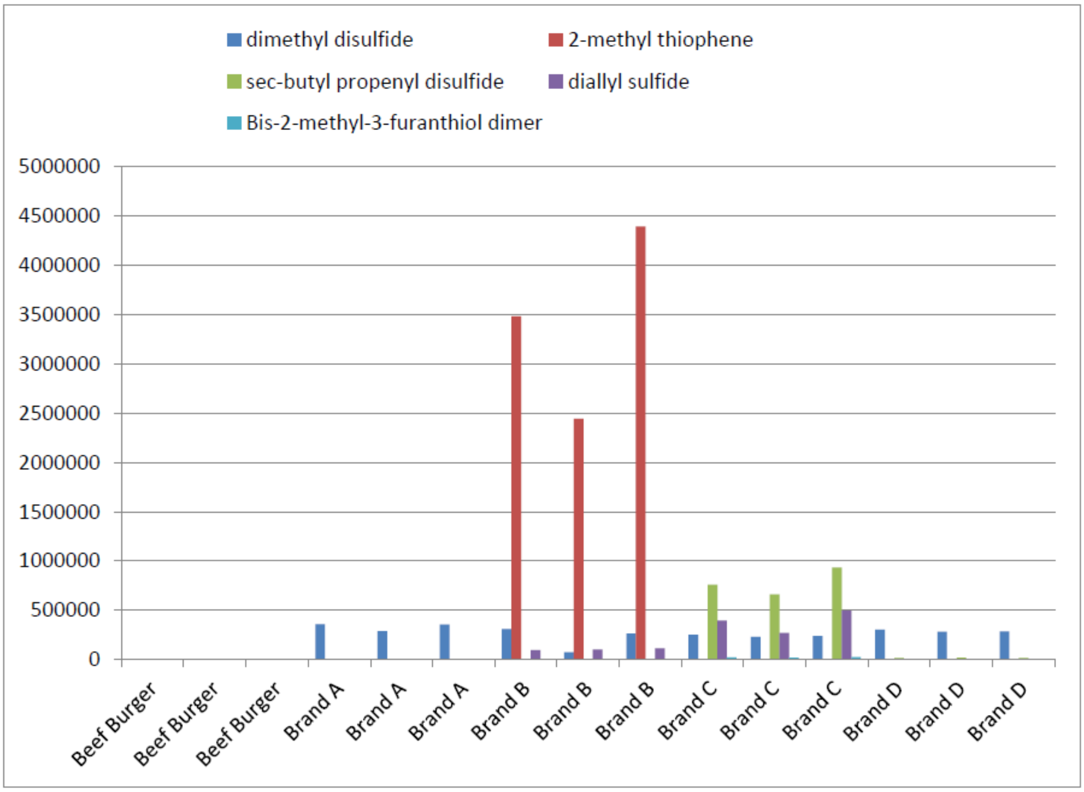

Figure 6. Added Sulfur Compounds in the Plant-based Hamburgers

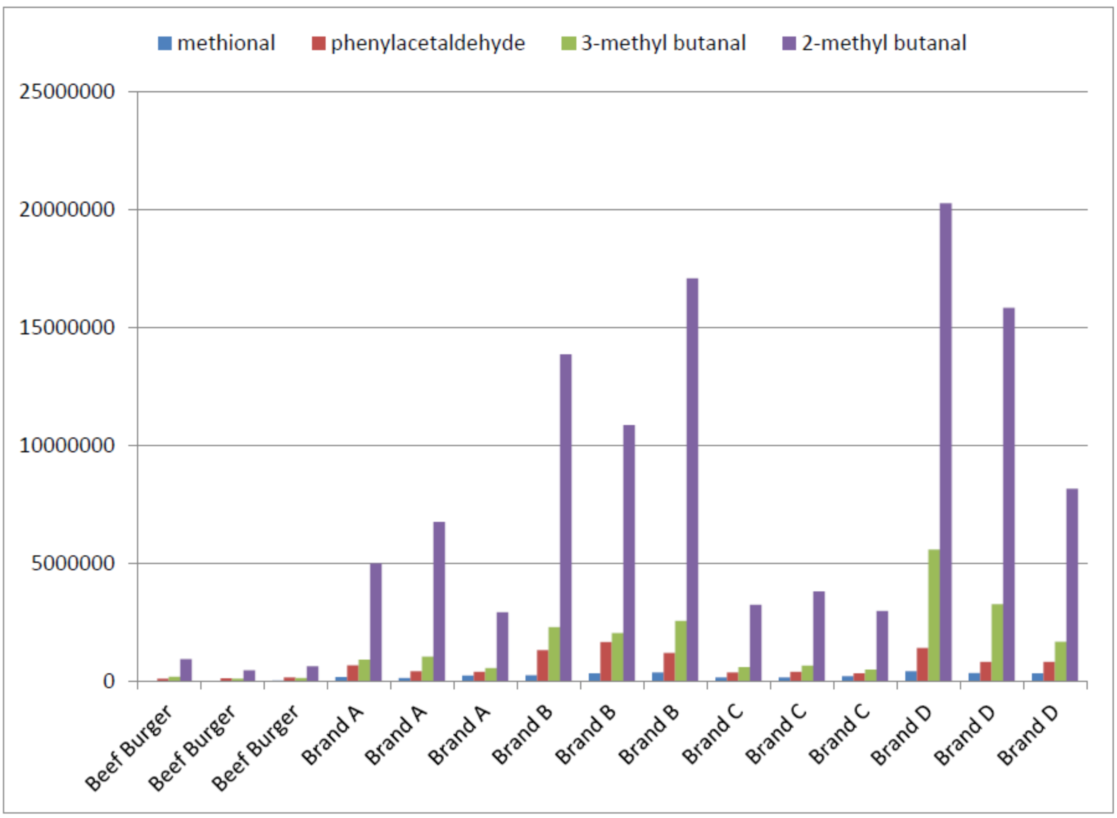

Figure 7. Comparison of Strecker Aldehyde Aroma Compounds in Beef versus Plant-based Hamburgers

4. Discussions

4.1 Aroma-active Compounds in Meat Hamburgers

This is the first list of compounds identified as important aroma contributors in hamburger. These compounds are easily detected using the SPME-GC-O method we applied here and some of these compounds have been reported as important contributors of beef flavor (Brewer et al., 2006). Other publications exist on stewed beef (Guth and Grosch, 1994) and roasted beef (Cerny and Grosch, 1992) which identified 16 and 22 compounds respectively. These same compounds were identified in this work; however, we identified an additional 8 new compounds. This was most likely accomplished because our approach using SPME enabled us to detect both the very volatile and semi-volatile compounds. The previous work cited above used solvent extraction in their methods and this most likely resulted in the omission of some very volatile compounds which we identified such as: methanethiol, trimethylamine, dimethyl sulfide, 2-methyl propanal, 3-methyl butanal, and diacetyl. Our results identified six compounds as most significant contributors to the aroma - diacetyl, methional, heptanal, octanal, furaneol, and 2-acetyl-2-thiazoline; followed by fifteen compounds with medium odor strength. 2-acetyl-2-thiazoline was also cited as a key aroma contributor in both roasted beef but not stewed beef. Further work in our lab is to recreate the hamburger aroma and we believe the 6 strong aroma contributors in combination with the 15 medium strength compounds will be key players in that work. Furthermore, we hypothesize that it may be as little as 5-7 compounds that can be combined to give the characteristic grilled hamburger aroma. This hypothesis is based on the experience that grilled hamburger aroma can be perceived at a significant distance from the source. And most compounds will fall below their odor detection threshold as a result of dilution in air.

The compound 2-acetyl-2-thiazoline is a low odor threshold compound with a very pleasant roasted, meaty aroma. This compound was previously identified as an important aroma contributor to beef broth (Tonsbeek et al., 1971). Hofmann et. al., 1996 studied the formation and stability of this compound in model systems and discovered that cysteamine and methyl glyoxal are two key precursors for the formation of this beef important aroma compound. In addition, these two compounds can form 2-acetyl-2-thiazoline under mild conditions and that additional heating can lead to its degradation. In our studies, we demonstrated that none of the plant-based burgers showed evidence of this important aroma compound in their products. The most likely reason would be a difference in the level of precursor compounds. Cysteamine comes from the decarboxylation of cysteine and methyl glyoxal can be produced by oxidation degradation of glucose (Thornally et al., 1999). Recently, Vliet et. al. (2022) applied a metabolomics comparison of the nutritional differences between plant-based meat and grass-fed meat and he observed significant differences in these protein sources. In this work, they study 18 different plant-based meat alternatives in the market and also included ground beef samples from 18 different grass-fed black angus cattle. With their analysis they measure cysteamine at high levels in all 18 angus cattle samples but this compound was absent in all plant-based samples. Cysteamine is present in many mammalian cells and is known to have a role in oxidative stress (Frazer-Pitt et al., 2018). This observation provides a key insight into the absence of this important beef aroma compound within the plant-based burgers.

4.2 Aroma-active Compounds in Plant-based Hamburgers

The aroma differences of the plant-based hamburgers compared to the beef hamburger was significant, except for Brand A which was described as similar to a frozen hamburger that was reheated – similar to real beef hamburger but not as fresh. The other plant-based products appeared to be taken the approach of creating a “whole hamburger plus condiment” experience instead of the more challenging approach to recreating the authentic hamburger aroma. This may be because of the limitations of ingredients and flavor stability; the developers took the approach of adding significant levels of flavors and ingredients (garlic and onion powders) to create a product with more flavor intensity. These products were more intense in flavor; however, they moved the flavor character away from the sweet, fatty, and buttery-meat character which provides that recognizable smell of hamburgers. Based on these evaluations, we assume that the ability to create an authentic hamburger aroma and flavor is a very challenging task. Our results are comparable to Sogari et. al. (2023) who found that consumers could easily recognize the difference in plant-based hamburgers compared to a meat or beef hamburger (Sogari et al., 2023; Hernandez et al., 2023). In addition, their findings indicated that consumers had a preference for the 100% beef hamburger compared to the available market plant-based burgers which included the Impossible burger and Beyond meat.

4.3 Principal Component Analysis and Hierarchical Cluster Analysis

PCA and HCA analysis of the volatile data are in agreement that Brand A plant-based hamburger is closets to the beef hamburger which correlates with our sensory panel. The agreement between our sensory and analytical data is reassuring that the GC-O work directed us to measure the most sensory relevant aroma molecules. The heat maps are good visual aids to show the difference in volatile compounds between the samples.

The beef hamburger is dominated by lipid derived aldehydes. Since these flavor compounds are derived by oxidative breakdown of the fats within the beef product, we can understand that plant-based products which use non-animal fat could be challenged in creating that characteristic fatty aroma compound profile. In addition, some of the important buttery note compounds diacetyl and acetoin, which are very important in the beef hamburger, may be derived by the fat and the plant-derived hamburgers trend lower in these buttery compounds. Researchers looking into the drivers of consumer preference in beef products have seen a correlation to the levels of these buttery compounds and overall consumer preference (O'Quinn et al., 2016). However, many of the plant-derived products were significantly higher in roasted compounds such as pyrazines. These differences in ratio of sweet-fatty to roasted compounds are key drivers in the aroma differences of plant-based vs beef hamburgers. There is more to learn about the ratios of those compounds in their contribution to the characteristic hamburger aroma. However, the compounds responsible for the characteristic grilled hamburger aroma have not been shared in the public domain and there is the opportunity for a publication on the in-depth understanding of this flavor as presented here.

In addition to aroma, plant-based meat analogues are also faced with the challenges of suppressing any negative or off-odors associated within the plant protein used in the matrix. For most plant proteins, lipid oxidations of polyunsaturated fatty acids are contributor of key off-odors (Ba et al., 2012; Zhogoeva et al., 2023). In addition, there are the presences of low odor threshold methoxy pyrazines that can contribute a pea-like flavor (Trindler et al., 2022; Trikusuma et al., 2020). Soy proteins can also develop the well documented reversion flavor (Smouse 1979). Taste is another consideration when working with plant proteins. These proteins are known to sometimes contribute negative taste aspects such as astringency and bitterness (Glaser et al., 2020). There have been negative taste attributes associated with these proteins as well, for instance saponins (Heng et al., 2006) and a recently discovered bitter peptide in pea protein (Ongkowijoyo et al., 2023). Indeed, the challenges to recreate animal meat aroma and flavor with plant-based proteins are numerous.

5. Conclusion

This study revealed the identification of the major odor-active compounds present in beef hamburgers using GC-O. Also, key differences in both the sensory and volatile compounds profile of leading plant-based burgers compared to a beef hamburger were presented in the experiments. The mechanisms of formation for these compounds were discussed and possible reasons for the differences in the plant-based burgers were characterized which provide opportunities for improvement in the aroma. These data highlight some of the key challenges faced in the development of plant-based meat analogues and provides insights into how the aroma of these products could be developed that would resemble closer to a beef hamburger. Overall, these findings show characteristic aroma compound and sensory challenges that plant-based hamburgers have to overcome in the replication of beef aroma. Next steps of research in our lab is focused on the role that reactive precursor compounds (amino acid derivatives and reducing sugars) play in the development of the characteristic beef hamburger aroma.

Author's contributions

Li Li Zyzak directed the experiments, sensory profiling, compound identification and wrote the manuscript; Joshua Zyzak performed GC-O, PCA analysis on data, sensory profiling, compound identification, and assist with the manuscript; Nathanial Britt performed GC-O, PCA analysis on data and sensory profiling; Lucy Jones performed GC-O and sensory profiling; Phillip Gilbert performed GC-O and sensory profiling; Callie Boogs performed GC-O and sensory profiling.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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