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Aroma and flavor profile of raw and roasted *Agaricus bisporus* mushrooms using a panel trained with aroma chemicals

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ABSTRACT

Agaricus bisporus is the most commonly consumed edible mushroom in the US, but research on its sensory properties is limited. This study characterized aroma and flavor of three raw and roasted *A. bisporus* mushrooms (white, crimini, and portobello) using quantitative descriptive analysis. Sixteen sensory attributes were chosen and included definitions and reference standards prepared with chemical solutions representing aromas perceived in the samples. All three raw *A. bisporus* possessed key sensory characters of mushroom, earthy, hay, soybean, potato, and woody aroma and flavors. Raw portobello and crimini had significantly higher ($p < 0.05$) flavor intensities in mushroom, earthy, dark meat, woody, and cabbage flavors, umami and bitterness taste, than white. When roasted, sensory profiles significantly ($p < 0.05$) shifted to dark meat, roasted, and fried notes, and portobello showed the highest intensity in dark meat flavor. Conversely, hay, woody, and earthy notes decreased in all roasted mushrooms. The results contribute to the growing body of research on mushroom sensory properties and potential use in savory products. The reference solutions could be adopted by other researchers or industry peers for *A. bisporus* sensory evaluation.

1. Introduction

Mushrooms have been a part of human diets and medicine for centuries. Currently, the mushroom industry has three main segments: cultivated edible, wild-harvested, and medicinal mushrooms (Robinson, Winans, Kendall, Dlott, & Dlott, 2019). Global mushroom production has grown dramatically with estimated commercial value over $75 billion in 2017, while edible mushrooms constitute over half of the economic value of the total global mushroom industry, (Robinson et al., 2019). More than 2,000 mushroom species are edible, while *Agaricus bisporus* is the most commonly consumed species, including three types: white and two brown (crimini and portobello) (Chakrabarti, Campbell, & Shonkwiler, 2019; Martins, 2016). In industry, white and brown *A. bisporus* mushrooms are produced from different strains. The brown ones, crimini and portobello, can be produced by either the same or different strains, with portobello being more mature than crimini. These mushrooms are generally used for culinary purposes. The most common consumption scenarios are raw white used in salads, and cooked brown crimini and portobello used in salads, entrées, burgers, and sandwiches.

Mushrooms contain unique health-promoting and disease-preventing dietary components as well as sensory attributes including distinctive aroma, taste, and texture. Nutritionally, mushrooms are low in calories, fat, sodium, and cholesterol, but high in proteins, carbohydrates, and dietary fiber (chitin and glucan) (Kalač, 2016a). A nutritional analysis of *A. bisporus* showed that chemical composition varied with time in storage and packaging atmosphere, with white mushrooms having higher nutritional value than brown when freshly harvested (Vunduk et al., 2018). Mushroom taste is attributed primarily to several water-soluble substances, including 5′-nucleotides, free amino acids, and soluble carbohydrates, which are associated with umami and sweet taste and can enhance meat-like flavor (Kalač, 2016a; Poojary, Orlien, Passamonti, & Olsen, 2017b; Wang, Li, Li, Wu, & Tang, 2018; Zhang, Venkitasamy, Pan, & Wang, 2013). Approximately 150 different volatile compounds have been identified in various mushroom species, with a series of aliphatic components such as 1-octen-3-ol, 3-octanol, 1-octanol, 1-octen-3-one, and 3-octanone identified as the major contributors to the characteristic mushroom aroma (Aisala et al., 2020; Cho et al., 2007; Combet, Henderson, Eastwood, & Burton, 2006; Costa, Tedone, De Grazia, Dugo, & Mondello, 2013; Grosshauser & Schieberle, 2013; Zhang et al., 2018; Zhou, Feng, & Ye, 2015).

It is surprising that research on mushroom sensory properties has been limited in some aspects. Detailed sensory properties is limited to a

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few mushrooms species including white button (*A. bisporus*), shiitake (*Lentinus edoles*), oyster (*Pleurotus spp.*), porcini (*Boletus edulis*), and several wild mushrooms (Table 1). Sensory properties of the most consumed mushrooms (white, crimini, and portobello) have either never (crimini and portobello) or only rarely been reported (Aisala et al., 2018; Chun, Chambers, & Han, 2020; Myrdal Miller et al., 2014), where white mushrooms were considered as a commercial standard (Aisala et al., 2018) or used for the purpose of meat replacement (Myrdal Miller et al., 2014). Most publications have focused on the sensory quality of mushrooms from a technological aspect, such as effects of growing substrate, storage of fresh mushrooms using modified atmosphere packaging, and processing methods (drying, blanching, sous-vide) (Antmann, Ares, Lema, & Lareo, 2008; Ares, Parentelli, Gámbaro, Lareo, & Lema, 2006; Djekic et al., 2017a; Djekic et al., 2017b; Jaworska & Bernas, 2009; Khaskheli et al., 2017; Liu, Vijayakumar, Hall III, Hadley, & Wolf-Hall, 2005; Maray, Mostafa, & El-Fakhrany, 2018; Omarini, Nepote, Grosso, Zygadlo, & Alberto, 2010; Politowicz, Lech, Sanchez-Rodriguez, Szumny, & Carbonell-Barrachina, 2017). Only a few publications focused on sensory properties of raw mushrooms independent from other foods (Chun, Chambers IV, & Han, 2020; Omarini, Nepote, Grosso, Zygadlo, & Albertó, 2010), while very few publications examined sensory properties of cooked mushrooms (Aisala et al., 2018; Boin, Azevedo, Nunes, & Guerra, 2016; Myrdal Miller et al., 2014; Phat, Moon, & Lee, 2016).

Detailed training procedure for descriptive sensory analysis were provided in a few studies where species were characterized (Aisala et al., 2018; Boin et al., 2016; Chun et al., 2020; Hagan et al., 2018), or subtle differences due to growing substrate or quality grade were investigated (Cho et al., 2007; Liu, Vijayakumar, Hall, Hadley, & Wolf-Hall, 2005; Omarini et al., 2010). On the other side, when a technological aspect was investigated, sensory attributes focused on overall profiles with emphasis on overall quality-related parameters such as appearance, overall aroma, flavor, and texture, instead of in-depth flavor attributes (Antmann et al., 2008; Ares et al., 2006; Dermiki, Phanphensophon, Mottram, & Methven, 2013; Djekic et al., 2017a, 2017b; Simon, Gonzalez-Fandos, & Tobar, 2005), while sensory profiling of mushrooms is essential for product selection and development. Additionally, only a few publications have a clear definition for each attribute used to describe mushroom sensory properties (Aisala et al., 2018; Boin et al., 2016; Cho et al., 2007; Chun et al., 2020; Hagan et al., 2018; Myrdal Miller et al., 2014; Omarini et al., 2010). References for each attribute are rare, and almost none of the studies have chemical references for flavor intensity level, except Aisala et al., 2018; Chun et al., 2020; and Zhang et al., 2018. Using references made with pure chemicals allows to reproduce studies when references using raw or processed foods are not available all year round or vary due to the nature of agricultural ingredients.

This study aimed to develop a descriptive flavor lexicon and chemical references for the most commonly consumed *A. bisporus* mushrooms. Three mushrooms, white, crimini, and portobello, were evaluated in both raw and roasted forms by a trained panel using quantitative descriptive analysis.

2. Materials and methods

2.1. Mushroom samples and preparation

White, crimini, and portobello mushrooms were freshly harvested and sent to Texas Woman's University next morning by a local mushroom supplier (J-M Farms, Inc., Miami, OK, USA). The fresh mushrooms were stored refrigerated (4 °C) and used within three days.

Mushrooms (with stipe) were rinsed with tap water to remove any loose growing medium from the cap, using a soft bristle brush when necessary. The cleaning procedure lasted for 5–10 s to avoid excess water retention by the mushrooms. The cleaned mushrooms were drained in a steel strainer sieve metal bowl with paper towels to fully dry. Once dried, the mushroom stipe was removed with a knife and discarded. The mushroom caps were sliced into a thickness of 0.5 cm using a mandolin slicer (Fullstar Houseware LLC, New York, NY, USA). The first and last slices (at both ends) were discarded, as they do not cook evenly compared to the rest of the mushroom caps. A stainless steel mixing bowl was sprayed with ~0.5 g of canola oil. The ratio of oil: mushrooms slices was approximately 1:200. Any excessive oil was wiped out with a paper towel. The sliced mushrooms were added to the bowl and were gently mixed with the sprayed canola oil with a large rubber spatula. The prepared mushroom slices were evenly spread on a sheet pan in a single layer with space between each slice, and then placed in an oven.

A convection oven (Blodgett SHO-100-G Natural Gas Single Deck Full Size, Blodgett, Essex Junction, VT, USA) was preheated to 176.7 °C under low fan. The cooking temperature and time had been optimized by one of the co-author with extensive experience (>10 years) as a chef in the restaurant industry. Oven temperature was controlled precisely and checked using an oven thermometer. When mushrooms were roasted for 2–3 min, small droplets of water developed on the surface of slices. At this point, the sheet pans were quickly removed from the oven. The mushroom slices were turned using a small rubber spatula and redistributed evenly on the sheet pan. The sheet pan was returned to the oven to finish cooking. The overall cook time varied depending on daily variance of mushroom moisture content and volume of the batch in the oven, but overall, mushrooms were roasted for 4–6 min. Portobello and crimini mushrooms needed to be turned more quickly and cooked faster than white mushrooms. Mushrooms were done cooking when much of the water had evaporated and browning had just begun. Moisture loss due to cooking in this study was 45%–50% by weight. Overcooking and excessive browning would result in chewy, potentially bitter products. Once done, the sheet pans were immediately removed from the oven. Roasted mushroom slices were quickly transferred to a holding vessel and placed in the serving cups (60 mL plastic cups with lids, AV Inc., Brooklyn, NY, USA), 4–5 slices per cup. The prepared mushroom slices were kept in an insulated food carrier (Cambro EPP400110, Cambro®, Huntington Beach, CA, USA). A tray of 2.4 L boiled water (~90 °C) was set on the bottom of the carrier, to hold temperature up to 3 h at 50–60 °C.

Raw mushroom slices were handled the same way as roasted slices, up to the oiling step. Cleaning and preparing roasted mushrooms took ~1 h while cleaning, slicing and serving raw mushroom took ~10 min.

2.2. Sensory panel training

All sensory procedures were reviewed and approved by the Texas Woman's University (TWU) Institutional Review Board (IRB). All participants were provided written, informed consent on IRB-approved forms. Nine panelists were recruited from students and faculty at TWU, including six females and three males with age 21–41. The panelists had descriptive sensory analysis experience in several other projects, where they had learned procedures and how to identify sensory attributes and develop terminology, definitions, and reference. They were trained to use intensity scales.

In this study, training for the panel included 12 sessions with approximately 90 min per session. In the first session, panelists were presented with all mushroom samples and were asked to describe their odor (smell, orthonasal aroma) and flavor (taste, retronasal aroma, and mouthfeel), followed by discussion. In the next sessions, the verbal descriptions of the lexicon were clarified upon the agreement of definitions. The reference mixtures of chemicals were tasted and their intensities were agreed upon using a continuous, unstructured line scale anchored 0 (left) and 10 (right) at both ends with 5 in the middle. Zero meant no perception; five meant a medium level of intensity; while 10 meant extremely strong intensity (beyond the intensity level that would be in the mushrooms). The final profile included 16 flavor attributes. Panelists then practiced rating the intensity of attributes in each

Table 1
Overview of the sensory profiling studies of mushrooms according to literature.

Mushroom species	Study objectives[a]	Sample preparation	Sensory attributes	Use of references and/or attribute definitions[b]	Citation
Agaricus bisporus (White, crimini, portobello)	Quality in storage, MAP	White mushroom: raw Portobello: raw	Overall (visual) quality, odor, color, taste, tenderness, shape of cap and size of cap; cap color, cap defect, gill color, gill defect, odor, odor defect	Agreement on the terms; no references	(Djekic et al., 2017a, 2017b)
	Sensory characteristics of four wild and one cultivated (white button) mushrooms	Sous vide cooking	Total odor intensity, mushroom, earth/soil, forest, cardboard, cooked carrot, mashed potato, roasted; sweetness, umami, bitterness, astringency, metallic, pungency; toughness, biting resistance, crumbliness, squeakiness	Chemical for mushroom-like (1-octen-3-ol, 3-octanone, methional), sweet, umami, bitter, astringent (aluminum sulfate hydrate), metallic (copper (II) sulfate hydrate); food references for rest; definitions for all attributes	Aisala et al. (2018)
	Flavor-enhancing properties of mushrooms in meat dishes; cooking differences	White mushrooms: seared, sautéed, steamed, and roasted	Overall aroma/flavor, raw mushroom, nutty, buttery, smoky, caramelized, burnt/charred, toasted/roasted, cardboard/paper, salty, umami, bitter, sweet, moisture	Definitions for all attributes	Myrdal Miller et al. (2014)
	Lexicon development for 11 fresh and dried mushrooms	Fresh and dried white, portobello, and others	Leather, moldy/cheesy, moldy/damp, mushroom, fishy, shellfish, woody, nutty, brown, green, cardboard, burnt/ashy, potato, umami, protein, yeasty, bitter, salty, sweet aroma, sour, astringent	Definitions for all attributes; chemical references for leather (2,3,4-trimethoxybenzaldehyde), moldy/cheesy (3-octanone), moldy/damp (2,3,4-trimethoxybenzaldehyde), umami, bitter, salty, sour, astringent; food references for the remaining attributes	Chun et al. (2020)
Lentinus edodes (Shiitake)	Quality in storage, modified atmosphere packaging	Shiitake: raw	Off-odor, gills color, gills uniformity, cap surface uniformity, presence of dark zones on the cap, and firmness	Agreement on the terms; no references	(Antmann et al., 2008; Ares et al., 2006)
Pleurotus spp. (Oyster)	Effect of growing substrate on sensory quality of oyster (*P. ostreatus*) and polypore (*Polyporus tenuiculus*)	Raw	Brown color, sweet, salt, bitter, sour, cereal, mushroom, astringent, pungency, hardness, fibrous, springiness	Definitions, chemical references for the four basic taste; food references for the remaining attributes	Omarini et al. (2010)
	Effect of blanching and drying methods on quality of dehydrated *P. ostreatus*	Dehydrated powder	Appearance, odor, color, texture, overall acceptability	N/A	Maray et al. (2018)
	Effect of growing substrate on sensory and composition of *P. sajor-caju*	Reconstituted dried oyster mushrooms and sautéed	Sweet pea, corn, beef broth, mushroom, sweet, and bitter; tough, fibrous, rubbery; color: light to dark	Food references	Liu et al. (2005)
	Aroma analysis (GC-MS, e-nose, sensory) of strains of three *Pleurotus* species: *P. ostreatus*, *P. citrinopileatus*, *P. djamor*	Samples placed in vials heated to 40 °C to smell	Mushroom-like, woody/fungal, earthy, musty, putrid, fishy, meaty (odor analysis only)	N/A	Zawirska-Wojtasiak, Siwulski, Mildner-Szkudlarz, and Wasowicz (2009)
	Sensory characteristics and consumer acceptability of king oyster (*P. eryngii*) and hedgehog (*Hydnum repandum*) mushrooms	Fresh or dried; raw or cooked	Raw: Aroma intensity, moldy odor, hardness; cooked: Intensity of aroma, hardness, umami, wateriness, chewiness, toughness, bitter aftertaste, umami aftertaste	Chemical references for umami and bitter; definitions for all 8 attributes	Boin et al. (2016)
	Sensory characteristics of *P. ostreatus*, *P. sajor-caju* and *Auricularia spp.* to be added in foods for children 2–5 years old	Dried powder boiled in water	Mushroom 1 & 2 flavor, cereals, boiled crab, sea food, fishy, tea, pungent, bitter, umami, astringent, chalky mouthfeel	Definitions for all attributes	Hagan et al. (2018)
Boletus edulis (Porcini)	Aroma analysis (GC-MS, GC-olfactometry) of fresh and dried porcini mushrooms	Raw fresh mushroom and dry mushroom powder	Raw: mushroom-like, earthy, grass-like, fatty, malty odor. Dried powder: mushroom-like, roasted, seasoning-like, cacao-like, sweaty, smoky odor	Chemical references for mushroom-like (1-octen-3-ol), earthy (geosmin), grass-like ((E)-2-octen-1-ol), fatty ((E,E)-2,4-decadienal), malty (3-methylbutanal), roasted (2,5-dimethylpyrazine), seasoning-like (estragole), cocoa-like (2-ethyl-3,5-dimethylpyrazine), sweaty (3-methylbutanoic acid), and smoky (2-methoxyphenol)	Zhang et al. (2018)
	Effect of blanching with pre-treatments on mushroom quality	Blanched and frozen samples, thawed prior to serving	Visual appearance, cell fluid leakage, color, texture, taste, and aroma	N/A	Jaworska and Bernas (2009)

(*continued on next page*)

Table 1 (*continued*)

Mushroom species	Study objectives[a]	Sample preparation	Sensory attributes	Use of references and/or attribute definitions[b]	Citation
Tricholoma matsutake (Pine-mushroom)	Aroma and flavor characterization of four grades of pine mushrooms by sensory, GC-MS and GC-O	Peeled and diced, raw	Sweet, salty, sour, bitter, umami, piney, floral, alcohol, meaty, moldy, wet soil, fishy, fermented, metallic, astringent	Chemical references for sweet, salty, sour, bitter, umami, astringent (tannic acid), moldy (1-octen-3-one); food references for all other attributes; definitions for all attributes	Cho et al. (2007)
Cantharellus cibarius (Chanterelle)	Effect of drying methods on volatiles and sensory profile of chanterelle mushrooms	Dried and fresh	Inner color, piece size; mushroom-like, fresh, smoked, spicy, nutty, earthy dry, burnt, woody, sharp, oxidative; hardness, sponginess	N/A	Politowicz et al. (2017)
Other mushrooms	Aroma of 11 wild species of mushroom by sensory and GC-MS	Mushroom powder and extracts in solution: headspace odor	Farm-feed, mushroom like, floral, honey-like, nutty, hay/herb	N/A	Guedes de Pinho et al. (2008)
	Characterize the umami taste in 17 Korean mushroom species by sensory, HPLC and e-tongue	Mushroom powder boiled in water for 5 min.	Sour, bitter, salty, rich, astringency, umami	Reference for umami (MSG solution at several concentrations)	Phat et al. (2016)

[a] Abbreviations: MAP: modified atmosphere packaging; GC-MS: gas chromatography-mass spectrometry; GC-O: gas chromatography-olfactometry; HPLC: high pressure liquid chromatography; MSG: monosodium glutamate.
[b] Chemical references for common taste attributes: sweet (sucrose), sour (citric acid), salty (sodium chloride), bitter (caffeine), umami (MSG).

mushroom sample over several sessions. Mushroom samples in the training sessions were served randomly to reduce bias from sample presentation order. The panel was trained in group and individual sessions until satisfactory discrimination, reproducibility, and concept alignment for each descriptor were determined.

2.3. Lexicon and reference development

Panelists generated the initial list of descriptors with mushroom samples according to their own experience and sensory attributes available in the literature (Aisala et al., 2018; Myrdal Miller et al., 2014). Then all descriptors were organized, discussed, and reorganized into a list. Vague, redundant, or repetitive terms were removed from the initial list. The final list of descriptors was determined and agreed upon by panelists before they were completely trained. All descriptors were elemental instead of a combination of several terms. The final list of the sensory attributes included 11 aroma/flavor (mushroom, earthy, dark meat, roasted, hay, soybean, potato, woody, fried, cabbage, and sulfur), four taste descriptors (salty, sweet, umami, and bitter), and one mouthfeel (astringent). With input from the panel, the panel leader created definitions for each attribute, and the final definitions represented a group consensus. The definition of each descriptor is shown in Table 2.

Each descriptor had a reference standard made from related chemicals that best represented the definition of the descriptor, with concentrations achieved by trial-and-error. Chemicals to make the reference standards were chosen from the literature (Aisala et al., 2018; Zhang et al., 2018). and from the volatiles identified in the samples in a parallel study (unpublished data). Detailed information about chemicals, purity, and manufacturers is shown in Table 2. All compounds were Food Grade from Sigma-Aldrich. Propylene glycol was used as the solvent to dilute flavor-related chemicals. The reference standards for the soybean and hay descriptors were not included in Table 2, because some chemicals were not commercially available. Based on their definition, the descriptors of soybean and hay were still used to rate the mushroom samples, because they appeared to be important characteristics for distinguishing among the mushrooms as well as the cooking methods.

2.4. Mushroom sample sensory evaluations

A randomized complete block design was used to serve both raw and oven roasted mushroom slices in one sitting. Raw mushroom slices were freshly prepared and served at room temperature, while roasted slices were kept in the food carrier with serving temperature ranging from 50 to 60 °C. Sample cups were placed onto individual serving trays and presented monadically for evaluation. References for each descriptor were served in individual 60 mL cups with lids containing ~40 mL of solution, respectively. Each panelist received a whole set of references which were used to help achieve concept adjustment and sample evaluation. Panelists were asked to smell and taste each chemical reference and compare its odor and flavor to the mushroom samples.

The tests were conducted in isolated booths illuminated with incandescent lighting. For each session, panelists evaluated six samples, which were split into two half sessions: three samples in the first half session with 15 min break, and another three samples in the second half session. Mushroom samples were presented randomly across the two sessions. The total evaluation time was approximately 45 min. The intensity of each attribute was evaluated across the samples on an unstructured line scale. Panelists rinsed their mouth between samples with bottled spring water (Nestle Pure Life Water, 240 mL). Each mushroom sample was evaluated in triplicate, meaning each panelist evaluated 18 samples in total on three different days. All instructions, text ballots, and data collection were carried out manually.

2.5. Statistical analysis

Preliminary exploratory analyses were first conducted to assess outliers and missing data, and normality assumption was verified using SPSS v. 25 (IBM SPSS Statistics, Armonk, NY, USA). Separation of means were performed across all six treatments and by either mushroom type or preparation method using the Fisher's Least Square significant difference test ($p \leq 0.05$) using Senpaq v.5.01 (Qi Statistics Ltd., Berkshire, UK). A principal components analysis (PCA) was performed using XLSTAT (Addinsoft, New York, NY, USA) to assess the similarities and differences among the mushrooms using the covariance matrix with Varimax rotation applied to the matrix of the mean intensity ratings across the samples.

3. Results and discussion

3.1. Mushroom flavor profile and references

In this study, 16 descriptors were developed for sensory evaluation of raw and roasted white, crimini, and portobello mushrooms. Definitions,

Table 2
list of descriptors used in the quantitative descriptive analysis panel, definition of each descriptor, reference chemical(s) that correspond to each descriptor, their preparation method, and intensity on a 0–10 unstructured line scale.

Descriptors	Definition	References, Manufacturer, and Purity	Reference Concentration/Preparation	Intensity
Mushroom	An aromatic generally associated with fresh raw mushrooms with some characteristics described as damp earthy and musty, for examples, white mushroom	1-octen-3-ol, Sigma-Aldrich; ≥98%; FCC and FG	Stock solution (SS): 1-octen-3-ol at 1000 mg/L in propylene glycol (PG). Reference solution (RS): adding 5 μL of SS to 100 mL of DI water to make 0.05 mg/L.	6
Earthy	An odor used to describe the perception of clean wet dirt associated with root vegetable, for examples, raw mushrooms, potato peel, beets	3-pyropylidenephthalide, Sigma-Aldrich; ≥96%; FG	SS: 3-pyropylidenephthalide at 100 mg/L in PG. RS: adding 2.5 μL of SS to 100 mL of NaCl solution (0.1%) to make 0.0025 mg/L.	3
Dark meat	A flavor compound of roast beef, pot roast, and cooked pork with aroma that is sulfurous, salty, or savory, for examples, beef, lamb, dark meat poultry	2-methyl-3-tetrahydrofuranthiol, Sigma-Aldrich; ≥97%; FG	SS: 2-methyl-3-tetrahydrofuranthiol at 100 mg/L in PG. RS: adding 1 μL of SS to 100 mL of DI water to make 0.001 mg/L.	4
Roasted	An aromatic that has the quality of roasted meat and vegetables with undertones of roasted hazelnut and cocoa, for examples, roasted chicken	2,5-dimethylpyrazine, Sigma-Aldrich; 98% 2,3-diethyl-5-methylpyrazine, Sigma-Aldrich; 99%; FG	SS1: 2,5-dimethylpyrazine at 1000 mg/L in PG. SS2: 2,3-diethyl-5-methylpyrazine at 1000 mg/L in PG. RS: adding 70 μL of SS1 and 30 μL of SS2 to 100 mL of DI water to make 0.7 mg/L of 2,5-dimethylpyrazine and 0.3 mg/L of 2,3-diethyl-5-methylpyrazine.	5
Hay	Herbal note associated with fresh hay, dry grass reminiscent of sage, for examples, black tea leaves	N/A	N/A	
Soybean	Beany musty note associated with fresh soybeans as well as soybean products, for examples, miso, tofu, soymilk	N/A	N/A	
Potato	Potato aroma associated with characteristics of cooked, boiled potatoes with sulfurous and earthy notes, for examples, boiled potato	Methional, Sigma-Aldrich; 96%	SS: methional at 10,000 mg/L in PG. RS: adding 1 μL of SS to 100 mL of DI water to make 0.1 mg/L.	5
Woody	Various wood aromas with notes of clove and tenacious woody spice, phenolic, and vanilla, for examples, oak, cedar wood	Eugenol, Sigma-Aldrich; ≥98%; FCC, FG Guaiacol, Sigma-Aldrich; ≥98% β-Caryrophyllene, Sigma-Aldrich; ≥80%; FCC, FG	SS1: eugenol at 1000 mg/L in PG. SS2: guaiacol at 1000 mg/L in PG. SS3: β-caryophyllene at 1000 mg/L in PG. RS: adding 40 μL of SS1, 80 μL of SS2, and 50 μL of SS3 to 100 mL of DI water to make 0.4 mg/L of eugenol, 0.8 mg/L of guaiacol, and 0.5 mg/L of β-caryophyllene.	5
Fried	Fatty notes developed in a product through high temperature cooking in fat/oil, for examples, French fried, potatoes, fried vegetables	Oleic acid, Sigma-Aldrich; 90%; Technical Grade	SS: oleic acid at10,000 mg/L in PG. RS: adding 100 μL of SS to 100 mL of DI water to make 10 mg/L.	5
Cabbage	Aroma typically associated with boiled, cooked cabbage; sulfurous, alliaceous aroma with a surface-ripened cheese topnote, for examples, cooked cabbage	Methanethiol, Sigma-Aldrich; 98%	SS: methanethiol at 1,000 mg/L in PG. RS: adding 75 μL of SS to 100 mL of DI water to make 0.75 mg/L.	5
Sulfur	Sulfurous notes typical of savory products; aroma and flavor associated with canned vegetables, for examples, cabbage, canned corn	Dimethyl sulfide, Sigma-Aldrich; ≥99%; FCC, FG	SS: dimethyl sulfide at 1,000 mg/L in PG. RS: adding 50 μL of SS to 100 mL of DI water to make 0.5 mg/L.	5
Salty	Elementary taste, for examples, table salt, savory products	Sodium chloride, Sigma-Aldrich	RS: dissolving 0.25 g sodium chloride to 100 mL of DI water to make 0.25 g/100 mL.	5
Sweet	Elementary taste, for examples, sucrose, sugarcane, sugar substitutes	Sucrose, Sigma-Aldrich Granular	RS: dissolving 3 g of sucrose to 100 mL of DI water to make 3 g/100 mL.	5
Umami	Elementary taste, characteristic savory note of broths and cooked meats, for examples, meat broth, mushroom	Monosodium glutamate (MSG), Sigma-Aldrich	RS: dissolving 0.05 g of MSG to 100 mL of DI water to make 0.05 g/100 mL.	5
Astringent	A dry, puckering mouthfeel sensation; effect of contraction of the mucous surfaces of the tongue and mouth cavity, mouth drying, as experienced in chewing some unripe fruits, for examples, tea, wine, quince, cranberry	Alum, Sigma-Aldrich; ≥98% Tannin, Sigma-Aldrich	RS: dissolving 0.075 g Alum and 0.1 g of Tannin in 100 mL DI water to make 0.075 g/100 mL of alum and 0.1 g/100 mL of tannin	5
Bitter	Elementary taste, effect of bitter compounds, quinine, caffeine, or citrus peel, for examples, coffee, dark chocolate, tonic drink, tea	Paracetamol, Sigma-Aldrich Quinine anhydrous, Sigma-Aldrich; ≥98.0%	SS: quinine at 0.0675 g/100 in DI water. RS: adding 0.0875 g of paracetamol and 1 mL of quinine SS to 100 mL of DI water.	5

references, reference preparation, and intensity levels are shown in Table 2. Four of the aroma descriptors including dark meat, soybean, cabbage, and sulfury are reported for the first time in this study, while the rest of the descriptors, including mushroom, earthy, roasted, hay, potato, woody, fried, salty, sweet, umami, bitter, and astringent, have been reported and used for mushroom descriptors (Aisala et al., 2018; Cho et al., 2007; Chun et al., 2020; Hagan et al., 2018; Myrdal Miller et al., 2014; Omarini et al., 2010). Descriptors in these papers were clearly defined to describe mushroom flavor, and our panel used these as a starting point, while developing their own wording to describe each attribute (Table 2). Definition is critical, and panelists can evaluate mushroom samples consistently by referring to the definition, especially when a chemical reference for an attribute does not exist, such as hay and soybean notes in our study.

Reference materials are used to establish a common vocabulary for various aromas and flavors. A reference standard can be any chemical or natural material that adequately represents the particular characteristic described (Krasner, 1995). Using examples can increase a panelist's understanding of important attributes; however, examples are less specific than references in terms of flavor perception (Lawless & Civille, 2013). Examples have a prominent component that illustrates a specific attribute, but examples themselves consist of multiple attributes, which may be confusing to panelists (Lawless & Civille, 2013). In other words, singular references such as single odor chemicals are preferred as long as they are practical, while examples are more general and can lead to interpretation. In addition, using chemicals as references has advantages of keeping consistent composition for the attribute and can easily be reproduced by others.

For reference standards to be universally utilized, they must yield a distinctive odor or flavor that transcends cultural and language differences, avoiding different levels of experience. Some descriptors needed only a single chemical that already yielded a distinctive odor on which a high percentage of observers could agree, while some descriptors required several chemicals to distinguish subtle but important characteristics and differences, as shown in Table 2. In this study, all reference standards and their intensity levels were consistent with all panelists. Chemical references for each attribute are rarely reported in descriptive sensory analysis (Table 1). For example, 1-octen-3-ol and 2,5-dimethylpyrazine have been used for mushroom and roasted aroma, respectively (Aisala et al., 2018; Zhang et al., 2018). Monosodium glutamate, sucrose, sodium chloride, caffeine, and tannic acid are commonly used as references for umami, sweet, salty, bitter, and astringent, respectively (Aisala et al., 2018; Chun et al., 2020; Omarini et al., 2010; Zhang et al., 2018). Chemical references for the rest of descriptors including dark meat, potato, woody, fried, cabbage, and sulfur appeared to be used for the first time to describe mushroom aroma.

3.2. Sensory profiles of A. bisporus mushrooms

The mean intensity values of aroma and flavor attributes of white, crimini, and portobello raw and roasted mushrooms are shown in Table 3. The intensities of most attributes were similar for both aroma and flavor of the same mushroom samples, resulting in a flavor profile for each mushroom that could be quantified using the same descriptors with some differences due to type or preparation. The attributes perceived to be present at the highest intensities were mushroom, earthy, hay, soybean, and woody notes for all raw mushrooms and both aroma and flavor. In contrast, cabbage and sulfur notes were minimally perceived. Dark meat, roasted, potato and fried notes were associated with the oven-roasted mushrooms. Sweet and umami taste were relatively high for all mushroom samples, regardless of raw or roasted preparation.

Raw crimini and portobello had the highest aroma and flavor of mushroom, earthy, dark meat, hay, and woody (significantly, except for mushroom flavor and hay aroma) compared with raw white. All types of roasted samples possessed significantly higher dark meat (only aroma), roasted and fried aroma and flavor, potato aroma, and salty taste compared with raw samples. Roasted crimini and portobello had significantly higher dark meat flavor and salty taste compared with roasted white and all raw samples. Cabbage flavor was higher in raw portobello. Umami, astringent, and bitter were higher in portobello raw and roasted, followed by crimini raw.

A PCA was performed to investigate the relationship between sensory descriptors of the six mushroom samples using the mean values of each descriptor's intensity for each mushroom sample (Fig. 1 A and B). PC1 explained 58% of the variance alone, while PC2 accounted for 32% of the variance. Raw crimini and raw portobello were clustered on the positive side of PC1, with high scores for mushroom, earthy, woody, sulfur, cabbage, and hay aroma and flavor; potato and soybean flavor; sweet, umami, and bitter taste, and astringent mouthfeel. Roasted crimini and portobello were on the positive side of PC2, with high scores for dark meat, roasted, and fried aroma and flavor, potato and soybean aroma, and salty taste. Most of descriptors had similar loadings for aroma and flavor, implying positive correlations. However, potato and hay flavor had high positive loading on PC1, but their aroma had high positive loading on PC2, implying aroma and flavor for these two descriptors were not correlated (Fig. 1A). Roasted white was located on PC1, opposite from raw crimini and Portobello; raw white was located on PC2, opposite from roasted crimini and portobello, indicating this sample had the lowest perceived intensities for all attributes.

The sensory quality of mushrooms is associated with aroma-active volatiles, non-volatile taste compounds, and phenolic compounds (Kalač, 2013, 2016c). Approximately 150 volatile compounds were identified in various mushroom species (Costa et al., 2013; Grosshauser & Schieberle, 2013; Guedes de Pinho et al., 2008; Yin et al., 2019). The volatiles can be grouped according to their chemical structure as alcohols, aldehydes, ketones, terpenes, acids, esters, sulfur-containing, and heterocyclic components. A series of eight-carbon aliphatic components such as 1-octen-3-ol, 3-octanol, 1-octanol, 1-octen-3-one, and

Table 3
Mean scores ± SD of aroma (A) and flavor (F) attributes for the quantitative descriptive analysis of raw and roasted white, crimini, and portobello mushrooms.

	White-Raw		White-Roasted		Crimini-Raw		Crimini-Roasted		Portobello-Raw		Portobello-Roasted		Pr > F
Mushroom-A**	3.69 ± 0.94	b	3.73 ± 1.22	b	4.51 ± 1.08	a	3.70 ± 1.31	b	4.57 ± 1.20	a	4.06 ± 1.31	ab	0.002
Mushroom-F	3.79 ± 1.31		3.56 ± 1.26		4.25 ± 1.06		3.94 ± 1.27		4.30 ± 1.24		3.99 ± 1.23		0.201
Earthy-A***	3.08 ± 1.13	c	3.08 ± 1.47	c	4.42 ± 1.23	a	3.35 ± 1.66	bc	4.21 ± 1.31	a	3.90 ± 1.69	ab	<.0001
Earthy-F***	3.40 ± 1.49	b	2.58 ± 1.33	c	4.24 ± 1.41	a	3.39 ± 1.34	b	4.43 ± 1.43	a	3.54 ± 1.58	b	<.0001
Dark Meat-A***	1.56 ± 1.21	b	2.56 ± 1.36	a	2.56 ± 1.68	a	2.83 ± 1.52	a	2.57 ± 1.82	a	3.03 ± 1.54	a	0.000
Dark Meat-F***	1.57 ± 1.38	c	2.55 ± 1.18	b	2.26 ± 1.50	bc	2.92 ± 1.54	ab	2.70 ± 1.78	b	3.52 ± 1.63	a	0.000
Roasted-A***	1.26 ± 1.38	b	2.83 ± 0.86	a	1.76 ± 1.73	b	3.13 ± 1.18	a	1.42 ± 1.44	b	3.06 ± 1.38	a	<.0001
Roasted-F***	1.10 ± 1.20	b	2.94 ± 1.14	a	1.54 ± 1.65	b	3.28 ± 1.34	a	1.42 ± 1.71	b	3.39 ± 1.45	a	<.0001
Hay-A	2.59 ± 1.03		2.58 ± 1.48		3.24 ± 1.65		2.77 ± 1.59		2.59 ± 1.64		3.07 ± 1.81		0.265
Hay-F*	2.79 ± 1.05	abc	2.31 ± 1.24	c	3.43 ± 1.61	a	2.37 ± 1.65	bc	3.09 ± 1.76	ab	2.62 ± 1.87	bc	0.023
Soybean-A	2.80 ± 1.04		3.00 ± 1.36		3.21 ± 1.48		3.12 ± 1.37		3.11 ± 1.62		3.34 ± 1.41		0.542
Soybean-F	2.78 ± 1.05		2.29 ± 1.00		3.11 ± 1.39		2.43 ± 1.32		3.01 ± 1.47		2.84 ± 1.48	c	0.104
Potato-A**	2.30 ± 1.01	c	2.89 ± 1.24	ab	2.72 ± 1.26	bc	3.32 ± 1.29	a	2.64 ± 1.31	bc	3.24 ± 1.37	a	0.002
Potato-F	2.77 ± 1.22		2.57 ± 1.26		3.05 ± 1.42		2.67 ± 1.36		3.03 ± 1.36		2.94 ± 1.40		0.473
Woody-A**	2.61 ± 1.43	b	2.71 ± 1.82	b	3.82 ± 1.51	a	3.02 ± 1.77	b	3.74 ± 1.58	a	3.02 ± 1.87	b	0.003
Woody-F***	3.05 ± 1.55	c	2.41 ± 1.28	d	3.76 ± 1.72	ab	2.99 ± 1.69	cd	4.03 ± 1.62	a	3.35 ± 1.80	bc	0.000
Fried-A***	0.42 ± 0.49	b	1.71 ± 1.46	a	0.53 ± 0.60	b	1.89 ± 1.54	a	0.56 ± 1.59	b	1.97 ± 1.64	a	<.0001
Fried-F**	0.60 ± 0.95	c	1.32 ± 1.11	ab	0.70 ± 0.80	bc	1.50 ± 1.41	a	0.69 ± 1.76	bc	1.82 ± 1.52	a	0.001
Cabbage-A	1.00 ± 0.98		1.03 ± 0.86		1.59 ± 1.63		1.27 ± 1.19		1.65 ± 1.41		1.39 ± 1.15		0.086
Cabbage-F*	1.52 ± 1.18	b	1.32 ± 0.96	b	1.70 ± 1.16	b	1.59 ± 1.26	b	2.24 ± 1.56	a	1.41 ± 1.15	b	0.013
Sulfur-A	1.24 ± 1.14		1.25 ± 1.01		1.66 ± 1.47		1.30 ± 1.06		1.46 ± 1.27		1.36 ± 1.25		0.559
Sulfur-F	1.46 ± 1.29		1.14 ± 0.90		1.72 ± 1.16		1.20 ± 1.05		1.57 ± 1.22		1.25 ± 0.95		0.073
Salty-F***	1.06 ± 0.87	c	1.77 ± 1.12	ab	1.37 ± 1.17	bc	1.82 ± 0.94	a	1.38 ± 0.93	bc	2.09 ± 1.22	a	0.000
Sweet-F	2.19 ± 1.08		2.05 ± 1.27		2.41 ± 1.39		1.79 ± 0.21		2.23 ± 1.37		1.93 ± 1.11		0.178
Umami-F*	2.96 ± 1.02	c	3.25 ± 1.21	abc	3.55 ± 1.08	ab	3.17 ± 1.18	bc	3.58 ± 1.10	ab	3.72 ± 1.21	a	0.031
Astringent-F*	1.62 ± 1.16	bc	1.23 ± 0.85	c	2.11 ± 1.25	ab	1.69 ± 1.29	bc	2.42 ± 1.63	a	1.89 ± 1.18	abc	0.024
Bitter-F**	1.24 ± 0.90	bc	1.01 ± 0.72	c	1.84 ± 1.18	ab	1.55 ± 0.99	bc	2.32 ± 1.51	a	1.70 ± 1.09	ab	0.004

*, **, ***: significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. SD: Standard Deviation.
Means (n = 9) followed by a different letter are significantly different using the Fisher's Least Significant Different test ($p < 0.05$).

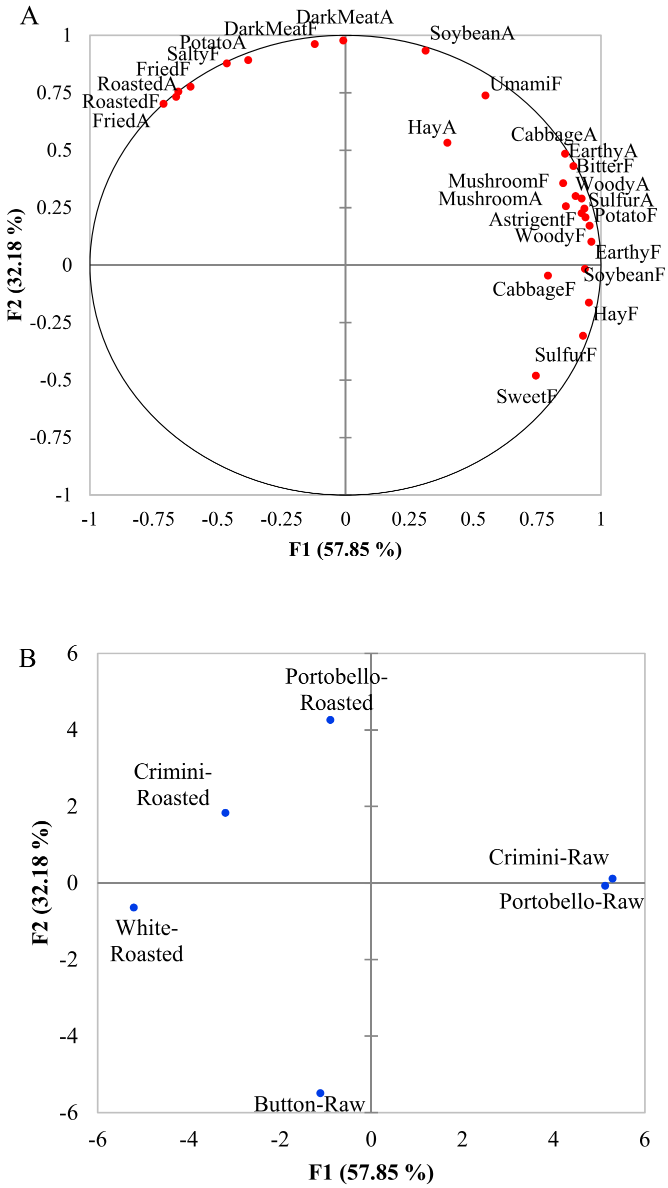

Fig. 1. Principle components analysis (PCA) plots of quantitative descriptive analysis of aroma (A) and flavor (F) attributes of six mushroom samples. A: Correlation of attributes; B: Sample scores.

3-octanone have been identified as the major contributors to the characteristic mushroom aroma (Combet et al., 2006; Grosshauser & Schieberle, 2013; Tasaki, Kobayashi, Sato, Hayashi, & Joh, 2019), and were identified in *A. bisporus* and other mushrooms (Combet, Henderson, Eastwood, & Burton, 2009; Grosshauser & Schieberle, 2013).

Sweet, salty, bitter, sour, and umami are recognized as the five basic tastes. In mushrooms, carboxylic acids contribute to sour taste, but sourness was not chosen as a descriptor by panelists in this study; sugars, polyols, and several amino acids form a sweet taste; while 5′-nucleotides, monosodium glutamate (MSG), and several other free amino acids and nucleotides elicit umami taste, and meaty, or savory flavor (Kalač, 2016b; Phat et al., 2016; Poojary, Orlien, Passamonti, & Olsen, 2017a; Wang et al., 2018; Zhang et al., 2013). The umami taste of edible mushrooms was widely investigated in recent years, and has shown a promising potential for use in the food spices industry (Phat et al., 2016). Mushrooms, and in particular *A. bisporus*, are considered a rich source of umami flavor, possessing a wide range of umami-inducing compounds including asp, glu, and 5′-mononucleotides in substantial quantities (Kalač, 2016b).

In addition, phenolic compounds, especially gallic acid, comprise a large group of mushroom constituents, which might be associated with mushroom bitterness and/or astringency (Kalač, 2013, 2016c). Astringency is usually seen as a negative mouthfeel factor; therefore, it needs to be taken into account when considering the complete flavor profile of portobello mushrooms.

The different flavor profiles of white, crimini, and portobello originate from the different levels of these volatile aroma compounds and non-volatile taste compounds. Nevertheless, human sense of flavor is neither fully linear nor analytical in the perception of complex mixtures of compounds in mushroom matrix. Various mixture interactions affecting flavor perception should be considered.

3.3. Effect of mushroom type on sensory quality

To compare the effect of mushroom type on sensory quality, four spider charts were created for a straight forward comparison. Three raw and three roasted mushrooms were compared and contrasted for aroma and flavor attributes (Fig. 2). The white sample had consistently lower intensities in most of the sensory attributes compared to the crimini and portobello regardless of preparation, raw or roasted.

Raw white had significantly lower levels ($p < 0.05$) of mushroom, earthy, dark meat, woody, and cabbage notes in aroma and significantly lower levels ($p < 0.05$) of earthy, dark meat, woody, cabbage, umami, and bitter flavor notes than raw crimini and portobello (Fig. 2 A & B); however, raw crimini and portobello had similar aroma and flavor profiles. The higher bitterness in crimini and portobello could be due to phenolic compounds reported higher in that mushroom type than in white (Vunduk et al., 2018). Once roasted, the sensory profiles of the three *A. bisporus* mushrooms changed. Roasted white, crimini, and portobello were only significantly different ($p < 0.05$) for earthy and cabbage aromas, although roasted white showed lower intensities in the majority of aroma descriptors compared to roasted crimini and portobello. Regarding flavor notes, the same descriptors as for raw mushrooms were lower in white than in crimini and Portobello, as well as astringent, while no significant difference ($p < 0.05$) of flavor profiles was observed between roasted crimini and portobello. In brief, the three *A. bisporus* mushrooms showed significant sensory profile differences as raw or roasted.

Considerable amount of studies associated with taste (non-volatiles) and aroma (volatile) compounds in mushrooms have been conducted for multiple species. There are major differences in volatile compound profiles between different species (Cho, Namgung, Choi, & Kim, 2008; Grosshauser & Schieberle, 2013; Guedes de Pinho et al., 2008; Yin et al., 2019; Zhang et al., 2018); nevertheless, the general distribution of volatiles in mushrooms is similar, with C8 aliphatic alcohols and carbonyl compounds being characteristic of raw mushrooms. Overall, the content of umami composition in edible mushrooms changes greatly with maturity stage and mushroom species (Cho, Seo, & Kim, 2003; Zhang, Wu, & Li, 2008). The three mushrooms used in this study were of the same species (*A. bisporus*) yet significantly different because they were from different strains, or maturity for crimini and portobello. The volatile 1-octen-3-ol with a typical mushroom odor, as well as the amino-acids Asp and Glu and the soluble sugar mannitol, increased in *A. bisporus* when harvested at a later maturity stage (Mau, Beelman, & Ziegler, 1993; Tsai, Wu, Huang, & Mau, 2007). Even though our study used different strains of *A. bisporus*, it is likely that similar changes occurred and explained the higher mushroom flavor and umami taste in crimini and portobello mushrooms. Studies on physiological and biochemical changes of mushrooms are very limited. It would be interesting to compare and contrast metabolic compositions of the three *A. bisporus* mushrooms.

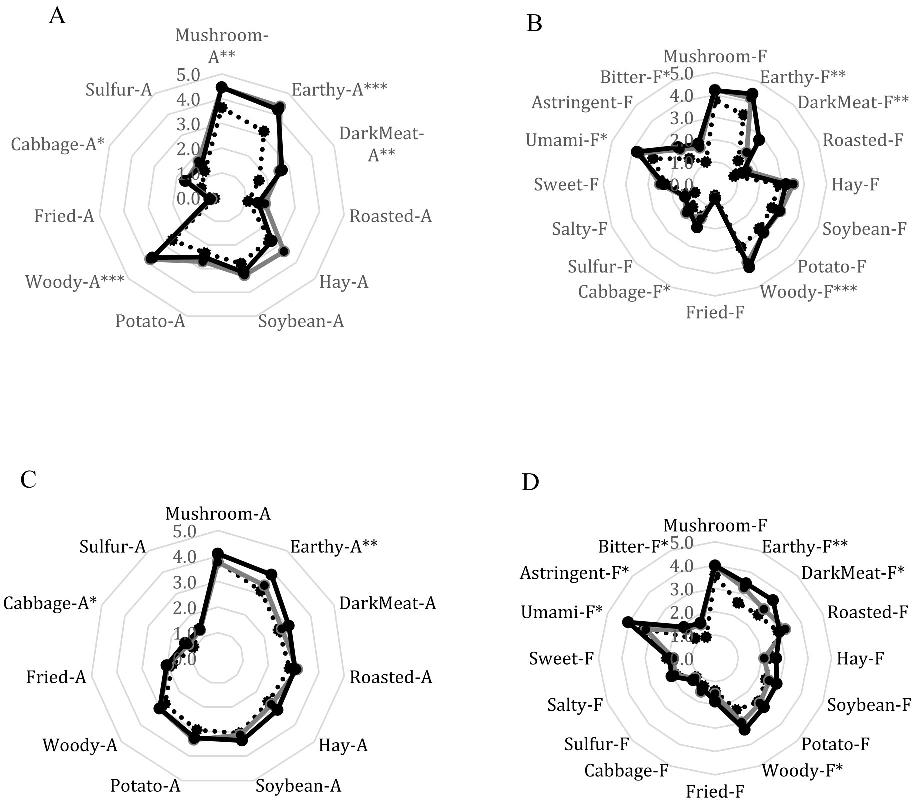

Fig. 2. Descriptive aroma and flavor profiles of white (••◆••), crimini (—◆—) and Portobello (—●—) mushrooms using a 0–10 line scale. A, B: raw; C, D: roasted. Note: *, **, ***: significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. A = Aroma and F = Flavor.

3.4. Effect of cooking methods on mushroom sensory quality

To compare the effect of cooking on mushroom sensory quality, six spider charts were created for a straight forward comparison. Raw and roasted were compared and contrasted by aroma and flavor qualities for each mushroom type (Fig. 3). Cooking had a significant effect ($p < 0.05$) on the sensory profiles, regardless of mushroom type. Overall, the roasted mushrooms had higher intensities of roasted, dark meat, and fried aroma and flavor as well as potato aroma. Conversely, earthy, woody flavors decreased once mushrooms were roasted. Compared to white and portobello, crimini lost more aroma and flavor intensity upon cooking, including mushroom and earthy aroma, earthy, hay, soybean, woody and sulfur flavors, as well as sweetness. Roasted white and portobello were also perceived saltier than raw, perhaps due to moisture loss in the process.

Generally, the cooking process will result in a loss of moisture and a subsequent concentration of constituents. The moisture content in *A. bisporus* mushrooms was reported to be, in decreasing order, white, crimini, and portobello (Dikeman, Bauer, Flickinger, & Fahey, 2005). Cooking also promotes chemical reactions such as the Maillard reaction of endogenic chemical components of sugars and amino acids under certain temperatures.

There is indirect evidence in the literature that the way mushrooms are prepared or cooked has a significant effect on flavor profiles, including volatiles and taste components. During the thermal process of *A. bisporus* mushrooms, the total content of volatile compounds increased from 15 to 50 mg per 100 g mushrooms, whereas the content of 3-octen-1-ol decreased by 10 fold (Grosshauser & Schieberle, 2013; MacLeod & Panchasara, 1983). The number and concentration of substituted pyrazines, furans, and pyrroles, which are typical products of the Maillard reaction, considerably increased during the drying of cepes and oyster mushrooms (Misharina et al., 2010). Regarding taste components, the temperature had a significant effect on some of the attributes in the flavor profile of a shiitake mushroom extract, and the extraction of 5′-ribonucleotides was higher at the higher temperature (Poojary et al., 2017b). It was also reported that the levels of free amino acids and 5′-nucleotides in a mushroom soup were higher in a microwaved soup than in a boiled or autoclaved soup, and more aroma-active volatile compounds were found in the boiled soup as well (Singh, Ghosh, & Patil, 2003). In brief, cooking has significant impact on mushroom aroma and flavor sensory profiles, regardless of mushroom types. Cooking mushrooms is known to increase their umami taste and “meat-like” flavor (Kalač, 2016a). In this study, roasted mushrooms not only created the highest overall aroma and overall flavor but also the highest meaty notes. Similar observation was reported in Myrdal Miller et al. (2014).

4. Conclusion

This sensory study developed a full flavor profile of raw and roasted white, crimini, and portobello mushrooms. The descriptive lexicon adds an important component to the current literature on the sensory properties of the mushroom species *A. bisporus*. The majority of the chemical references used in this study for each descriptor is reported for the first time, which has an advantage to offer consistent composition and be reproducible in different labs. Significant sensory differences were found among the three strains in the same mushroom species, *A. bisporus*, and more differences in sensory properties were found for all samples when they were roasted. The intensities of sensory descriptors increased when the samples were roasted. This study also served as a demonstration of the effect of the cooking method on the flavor profile of *A. bisporus* mushrooms. The limit of this study was that texture properties of *A. bisporus* mushrooms were not included, which should be included in a future study. It should be pointed out that temperature has an impact on the perceived product sensory quality; the flavor and texture characteristics and flavor delivery mechanism change from bite

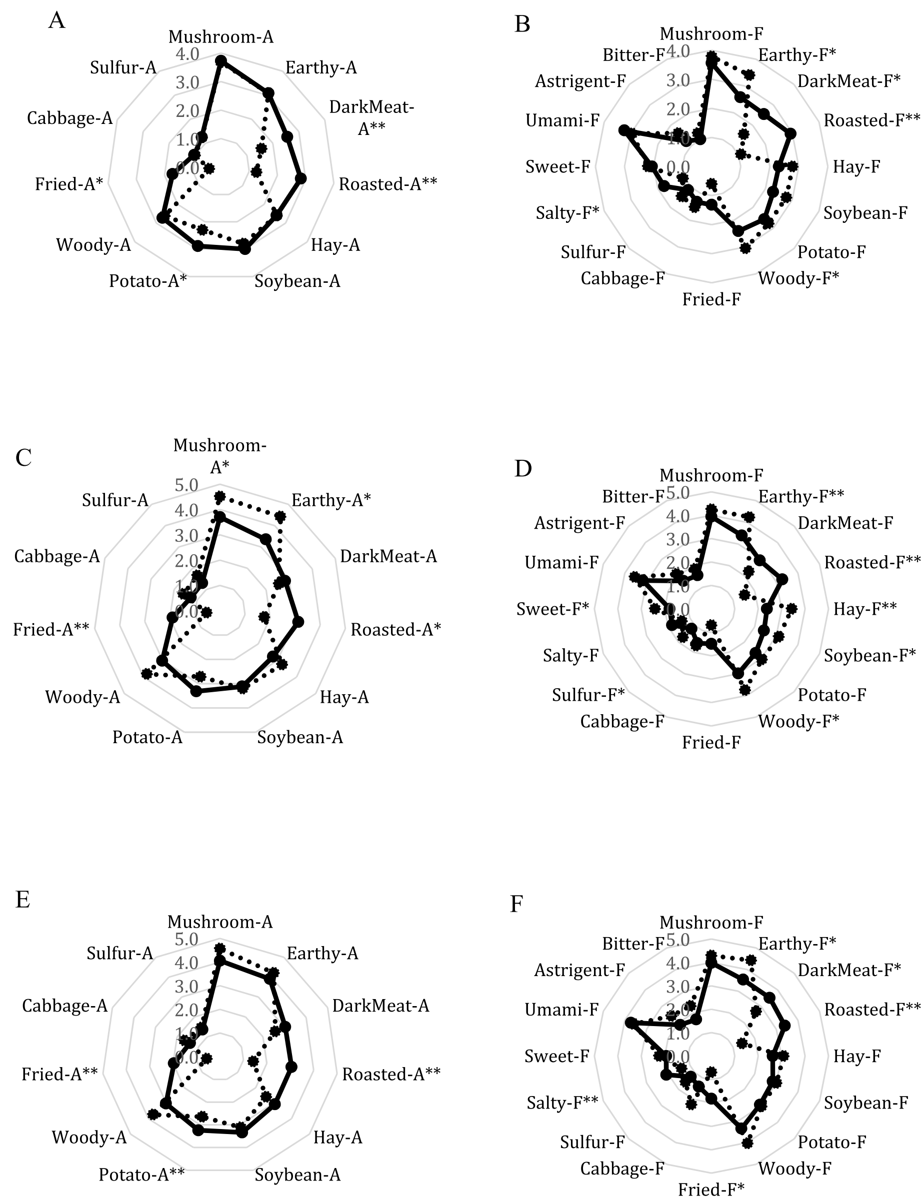

Fig. 3. Descriptive aroma and flavor profiles of raw (···◆···) and roasted (—●—) mushrooms using a 0–10 line scale: white (A, B), crimini (C, D) and portobello (E, F). Note: *, **, ***: significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. A = Aroma and F = Flavor.

to bite due to heterogeneous nature of mixed dishes. Therefore, the experimental conditions need to be well controlled.

CRediT authorship contribution statement

Xiaofen Du: designed the entire study, guided the research work in each step, analyzed the data, and wrote the manuscript. **Joanna Sissons:** developed and prepared all the reference standards for QDA of mushrooms. She also collected QDA final evaluation data and analyzed the data with SPSS and XLSTAT software. **Marcus Shanks:** prepared mushroom samples, trained the sensory panel, and conduced QDA study. **Anne Plotto:** analyzed the data and thoroughly reviewed the manuscript.

Declaration of competing interest

No conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2020.110596.

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