Volatile Profiles of Log-Cultivated Shiitake (*Lentinula edodes*) on Four Hardwood Species by HS-SPME/GC-MS

Chih-Hung Lee [a,b], Chun-Ya Lin,[c] Su-Ling Liu,[d] Ying-Ju Chen [e,*] and Sen-Sung Cheng [a,d,*]

The volatile profiles of shiitake mushrooms (*Lentinula edodes*) cultivated on logs of *Liquidambar formosana*, *Cinnamomum burmannii*, *Quercus glauca*, and *Q. variabilis* were analyzed using headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME/GC-MS). Distinct headspace volatile compositions were observed among log species and HS-SPME extraction temperatures. For fresh mushrooms analyzed at 25 °C, samples grown on *L. formosana* and *Q. variabilis* contained abundant linalool, whereas those cultivated on *C. burmannii* and *Q. glauca* were dominated by C8 alcohols such as 3-octanol. When fresh mushrooms were analyzed at 100 °C, the profiles shifted toward long-chain fatty acids, including *n*-hexadecanoic acid and linoleic acid. Dried mushrooms were analyzed only under 100 °C HS-SPME condition and exhibited similar patterns across all log species, with linoleic acid and *n*-hexadecanoic acid as the predominant components. These findings suggest that log species and HS-SPME extraction temperature are associated with distinct headspace volatile profiles, possibly through differences in substrate-derived chemical environments, temperature-dependent volatilization, and compound transformation, thereby shaping the potential aroma characteristics of log-cultivated shiitake mushrooms.

DOI: 10.15376/biores.21.3.6398-6415

Keywords: Cinnamomum burmannii; Liquidambar formosana; Odor composition; Quercus glauca; Quercus variabilis; Shiitake mushroom; Volatile compounds

Contact information: a: School of Forestry and Resource Conservation, College of Bio-Resources and Agriculture, National Taiwan University, Taipei 106319, Taiwan; b: Academy of Arts & Design, Tsinghua University, Beijing 100084, China; c: Department of Wood Based Materials and Design, College of Agriculture, National Chiayi University, Chiayi 600355, Taiwan; d: The Experimental Forest, College of Bio-Resources and Agriculture, National Taiwan University, Nantou 557004, Taiwan; e: Forest Products Utilization Division, Taiwan Forestry Research Institute, Ministry of Agriculture, Taipei 100051, Taiwan; Corresponding author: yingju@tfri.edu.tw; sscheng@ntu.edu.tw

INTRODUCTION

The shiitake mushroom (*Lentinula edodes*) is a well-known edible fungus valued for its characteristic aroma and nutritional benefits (Zhang *et al.* 2016; Piska *et al.* 2017; Morales *et al.* 2019). Its volatile compounds, including alcohols, ketones, and sulfur-containing molecules, contribute to distinctive sensory attributes that determine consumer preference and product quality (Zhang *et al.* 2010; Politowicz *et al.* 2018). In Taiwan, log cultivation of shiitake mushrooms not only supports sustainable forest utilization but also adds economic value to afforested lands (Huang *et al.* 1988; Huang *et al.* 1990; Lu 2017). The selection of appropriate log species is therefore crucial for optimizing both yield and

flavor quality (Tisdale *et al.* 2006; Chiou and Tsao 2017).

Wood composition plays a pivotal role in determining the growth environment and metabolic activity of shiitake mycelia (Li *et al.* 2019). Previous studies have shown that bacterial or substrate volatiles can alter fungal metabolite production (Orban *et al.* 2023), implying that wood-derived compounds could similarly influence the biosynthesis of odor-causing molecules during fruiting body development. In Taiwan and East Asia, *Liquidambar formosana*, *Cinnamomum burmannii*, *Quercus glauca*, and *Q. variabilis* are among the most common or suitable hardwood species used for shiitake log cultivation, owing to their moderate density, moisture retention, and stable nutrient composition (Huang *et al.* 1988; Huang *et al.* 1990; Lu 2017). These species exhibit notable variations in essential oil and extractive compositions, including phenolic, terpenoid, and fatty acid constituents characteristic of each genus (Al-Dhubiab 2012; Ouyang *et al.* 2016; Burlacu *et al.* 2020). Such chemical diversity may influence the metabolic environment during shiitake cultivation and contribute to differences in volatile profiles among mushrooms grown on different logs.

Previous studies have examined how drying, heating, and cultivation conditions modulate shiitake volatiles, showing that drying temperature and method can alter the relative abundance of lipid-derived volatiles (*e.g.*, 1-octen-3-ol) and linoleic-acid-related products (Politowicz *et al.* 2018; Lu *et al.* 2022). Studies incorporating odor-activity evaluation or gas chromatography-ion mobility spectrometry (GC-IMS) further indicate that physical or thermal processing enhances fatty-acid-derived notes while modifying sulfurous components (Hu *et al.* 2024; Xie *et al.* 2024). Electronic-nose approaches combined with multivariate analysis have also been applied to distinguish volatile fingerprints of mushrooms under different processing or storage conditions (Guo *et al.* 2022). However, most previous investigations have compared cultivation substrates or focused on processing conditions, whereas studies based on the use of different log species as cultivation materials remain limited.

Against this background, the present study characterizes the headspace volatile composition of *Lentinula edodes* cultivated on four hardwood species—*L. formosana*, *C. burmannii*, *Q. glauca*, and *Q. variabilis*—under ambient and heated conditions using headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME/GC-MS). The analysis compares volatile profiles across log species and temperature treatments, which were designed to simulate aroma release under room and cooking conditions, reflecting the sensory experience during consumption. It identifies major compound classes and interprets compositional differences by referring to previously recognized lipid- and sulfur-related odor compounds that are known to shape shiitake aroma. Additionally, odor characteristics of representative compounds were interpreted based on previous reports and odor databases to provide qualitative context for the chemical results, acknowledging that quantitative sensory evaluation and OAV assessment were not conducted in this study. These findings provide fundamental insights into how cultivation materials affect mushroom aroma characteristics and establish a baseline for future studies integrating chemical analysis with sensory perception.

EXPERIMENTAL

Materials

Shiitake mushrooms

Fresh shiitake mushrooms (*Lentinula edodes*, product 922) were cultivated on logs of four tree species, including *Liquidambar formosana* (18 years), *Cinnamomum burmannii* (14 years), *Quercus variabilis* (26 years) and *Q. glauca* (22 years), at the Experimental Forest of National Taiwan University. The samples were collected from the Neimaopu and Heshe working circles of the Experimental Forest, as recorded in the original experimental report. For each log species, fruiting bodies were collected from multiple logs and pooled for analysis. Fruiting bodies with similar external maturity were selected based on the practical experience of the Experimental Forest staff. Growth cycle and fruiting body size were not quantitatively recorded. After harvest, mushrooms were transported to the laboratory and stored at -20 °C until analysis. The four log species were selected based on their practical use or suitability for shiitake log cultivation rather than matched tree age. Therefore, possible effects of tree age on wood chemical composition and mushroom volatile profiles could not be excluded and are acknowledged as a limitation of this study.

Chemicals used for identification

The α-pinene (purity, 99%), *p*-cymene (99%), limonene (97%), γ-terpinene (98%), linalool (97%), and borneol (98%) were purchased from Acros; 1-octen-3-ol (98%) was purchased from Alfa Aesar; 3-octanone (98%), 3-octanol (99%) and camphor (97%) were purchased from Aldrich; 1,8-cineole (98%) was purchased from TCI (Japan); and trans-ocimene (90%) and naphthalene (98%) were purchased from Fluka.

Drying Process

Fresh mushrooms were dried using a modified method (Huang *et al.* 1988; Huang *et al.* 1990). Drying was conducted sequentially at 45 °C for 8 h, 55 °C for 8 h, 60 °C for 4 h, 70 °C for 2 h, and 80 °C for 1 h, totaling 23 h. Dried samples were stored in sealed bags for analysis. In the present study, dried samples were analyzed only under the 100 °C HS-SPME condition; dried mushrooms were not analyzed at ambient temperature. Therefore, the dried-sample results should be interpreted as volatile profiles of dried mushrooms under simulated hot-preparation conditions rather than as the effect of drying alone. Moisture content was measured for fresh mushroom samples as supporting sample information. For dried mushrooms, complete moisture-content records were not available for all log species; therefore, moisture content was not included as a quantitative factor in the statistical analysis.

Adsorption of Odor-Causing Components

Solid-phase microextraction (SPME) with a 100 μm polydimethylsiloxane (PDMS) fiber was used to adsorb headspace odor compounds from mushroom powder. The procedure was modified from Lagalante and Montgomery (2003). In this study, "fresh mushrooms" refer to undried fruiting bodies stored at -20 °C after harvest, whereas "dried mushrooms" refer to samples subjected to the drying process described above. Both fresh and dried mushrooms were ground under liquid nitrogen before HS-SPME extraction, and the resulting powders were placed in 20 mL headspace vials. Fresh mushroom samples powders were analyzed at two HS-SPME extraction temperatures, 25 °C and 100 °C, for

30 min. Dried mushroom powders were analyzed only at 100 °C for 30 min to simulate hot preparation of dried shiitake mushrooms. After extraction, the SPME fiber was immediately desorbed in the GC injection port for GC-MS analysis. In this study, replicate analyses were based on individual fruiting bodies. Each injection used powder prepared from one individual mushroom, and each powdered sample was analyzed once. Thus, the replicate number represents independent mushroom samples rather than repeated injections of the same sample. Preliminary trials were conducted for dried mushrooms at ambient temperature; however, the headspace signals were too weak for reliable profiling. Therefore, dried samples were analyzed only at 100 °C in the final experimental design.

Analysis of Odor-Causing Components

GC-MS analysis was conducted based on the method by Zhou *et al.* (2020) with slight modifications. A Polaris Q GC-MS System (Thermo) equipped with a DB-5ms fused silica capillary column (30 m × 0.25 mm × 0.25 μm) was used. Helium (5N5) served as the carrier gas at 0.80 mL/min. The injection port temperature was 250 °C, and the MS ion source temperature was 200 °C, with a mass range of *m*/*z* 33 to 450 amu. The temperature program started at 40 °C (held for 3 min), increased to 90 °C at 5 °C/min, and then to 230 °C at 10 °C/min, where it was held for 7 min. A split ratio of 10:1 was used for injection.

The components were identified from the mass spectra by comparing these spectra with the Wiley 7.0 and National Institute of Standards and Technology (NIST) 2.0 databases, and with an author constructed standards database; an arithmetic index (AI) was employed to perform the comparison. (Shen *et al.* 2006; Adams 2007; Babushok *et al.* 2011; Hang *et al.* 2012; Lan *et al.* 2017; Politowicz *et al.* 2018; Kim *et al.* 2020). Identifications were verified using the standards, and the percentage of each odor-causing component was calculated on the basis of the peak areas in the gas chromatogram, as follows,

$$AI = 100 \times \{n + [RT(x) - RT(n)]/[RT(n+1) - RT(n)]\} \quad (1)$$

where $RT(n)$ and $RT(n+1)$ are the retention time of *n*-alkanes with carbon number n and $n+1$, respectively, and $RT(x)$ is the retention time of an unknown compound x, with $RT(n) \leq RT(x) \leq RT(n+1)$.

Statistical Analysis

All statistical analyses were conducted using Python 3.13 with the SciPy library. Relative contents of volatile compounds were calculated based on GC peak area percentages and are reported as mean ± standard deviation where replicate data were available. Independent-samples *t*-test were used to compare selected volatile compounds between fresh and dried treatments for each log species when both treatment groups contained at least two replicates. The confidence interval was set at 95% ($p < 0.05$). Because not all compounds were detected across all samples and treatments, statistical comparisons were performed only for compounds with sufficient replicate data.

RESULTS AND DISCUSSION

Analysis of Odor-Causing Components in Fresh Shiitake Mushrooms Cultivated on Logs of Various Tree Species

The volatile constituents of fresh shiitake mushroom cultivated on four hardwood log species were analyzed using headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME-GC-MS). The results are presented in Fig. 1, Table 1, and Fig. 2.

At ambient temperature (25 °C), 21 compounds were identified in mushrooms grown on *L. formosana* logs (Lf), accounting for 97.6% of the total volatiles. The dominant odor-causing components were linalool (43.9%), 1-octen-3-ol (10.9%), and limonene (8.6%). For *C. burmannii* logs (Cb), 17 compounds were identified, comprising 100% of the total volatiles. The major components were 3-octanol (33.3%), 1-octen-3-ol (10.9%), 3-octanone (10.5%), and linalool (8.9%). In mushrooms cultivated on *Q. variabilis* logs (Qv), 26 volatiles were detected, representing 97.2% of the total. The dominant compounds were linalool (24.0%), dimethyl trisulfide (23.7%), dimethyl disulfide (12.5%), and 1-octen-3-ol (8.9%). For *Q. glauca* logs (Qg), 13 compounds were identified, accounting for 93.9% of the total volatiles, with 3-octanol (32.7%) and 3-octanone (30.1%) being the most abundant.

According to Politowicz *et al.* (2018), 1-octen-3-ol is one of the major volatile compounds in fresh shiitake mushrooms, accounting for approximately 20% of the total volatiles. In this study, 1-octen-3-ol was consistently detected under all log conditions, ranging from 3.9 to 10.9%. Linalool was also present in all samples, with its relative content highest in Lf (43.9%) and lowest in Qg (1.9%); however, it was not reported by Politowicz *et al.* (2018).

In addition, α-pinene, 3-octanone, 3-octanol, *p*-cymene, limonene, 1,8-cineole, *p*-propyltoluene, 1,2,4-trithiolane, and 2-phenyl-2-butenal were found across all samples, although with variable proportions. Sulfur-containing compounds, particularly dimethyl disulfide and dimethyl trisulfide, were notable in Qv, whereas in the other samples they appeared only in trace amounts (*e.g.*, 6.0% dimethyl trisulfide in Lf) or were undetected.

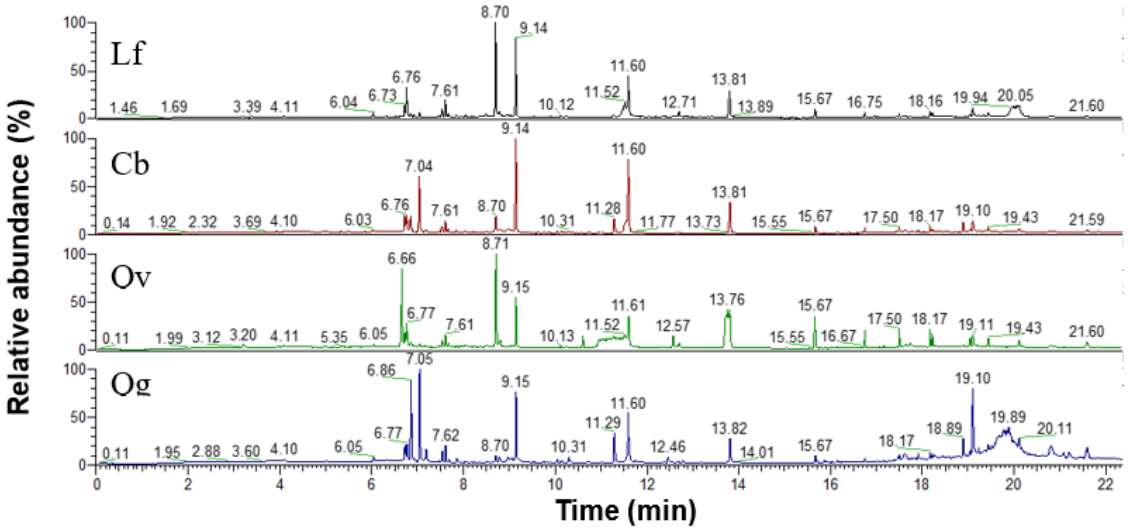

Fig. 1. Gas chromatograms of fresh *L. edodes* cultivated on four logs at ambient temperature. *Lf: L. formosana; Cb: C. burmannii; Qv: Q. variabilis; Qg: Q. glauca*

Previous studies have identified lanthionine as a sulfur-containing precursor that can decompose to form dimethyl disulfide and dimethyl trisulfide (Zhang *et al.* 2010). The higher relative abundance of sulfur-containing volatiles in Qv may therefore be related to differences in substrate-derived chemical environments during mushroom development. However, because precursor compounds and metabolic pathways were not directly measured in this study, this interpretation should be regarded as a possible explanation rather than direct evidence of pathway regulation. Overall, the compositional patterns indicate that the log species used for cultivation were associated with distinct volatile profiles in fresh *L. edodes* under ambient conditions.

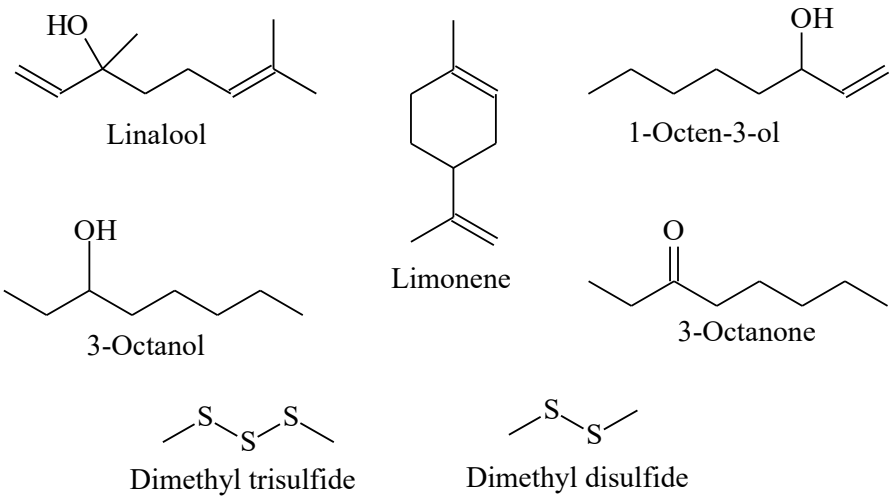

Fig. 2. Chemical structures of the primary odor-causing components of fresh *L. edodes* cultivated on four logs at ambient temperature

Table 1. Percentages of Odor-causing Components of Fresh *L. edodes* Cultivated on Four Tree Log Types at Ambient Temperature

AI [a]	rAI [b]	Compounds	Specimens				Identification [d]
			Lf [c]	Cb	Qv	Qg	
782		Dimethyl disulfide	-	-	12.5 ± 12.7	-	MS
936	932	α-Pinene	3.0 ± 0.6	1.3	1.4 ± 0.1	1.4 ± 0.3	MS, AI, ST
973		Dimethyl trisulfide	6.0 ± 6.7	-	23.7 ± 3.4	-	MS
980	974	1-Octen-3-ol	10.9 ± 2.4	10.9	8.9 ± 2.4	3.9 ± 1.4	MS, AI, ST
985	979	3-Octanone	1.9 ± 0.4	10.5	1.5 ± 0.0	30.1 ± 7.7	MS, AI, ST
997	988	3-Octanol	2.4 ± 0.2	33.3	1.5 ± 0.1	32.7 ± 0.0	MS, AI, ST
1027	1020	*p*-Cymene	4.4 ± 1.1	4.2	2.3 ± 0.0	4.5 ± 0.5	MS, AI, ST
1032	1024	Limonene	8.6 ± 1.2	5.3	3.9 ± 0.3	5.5 ± 0.1	MS, AI, ST
1036	1026	1,8-Cineole	1.8 ± 0.3	2.2	0.9 ± 0.1	1.0 ± 0.1	MS, AI, ST
1047	1044	*trans*-Ocimene	0.3 ± 0.4	2.0	0.7 ± 0.2	-	MS, AI, ST
1053		*p*-Propyltoluene	1.1 ± 0.3	0.6	0.7 ± 0.2	0.6 ± 0.2	MS
1068		*o*-Propyltoluene			-	-	0.2 ± 0.3	-	MS
1088		1-Ethyl-3,5-dimethylbenzene			-	-	1.2 ± 0.2	-	MS
1100	1095	Linalool			43.9 ± 3.2	8.9	24.0 ± 4.2	1.9 ± 0.3	MS, AI, ST
1106	1095	1,2,4-Trithiolane			2.7 ± 0.6	0.8	2.3 ± 0.9	1.1 ± 1.5	MS, AI
1154	1141	Camphor			0.8 ± 0.2	0.5	0.4 ± 0.0	-	MS, AI, ST
1178	1165	Borneol			0.7 ± 0.2	-	0.2 ± 0.0	-	MS, AI, ST
1188		1-Nitropropylbenzene			-	1.0	-	0.5 ± 0.8	MS
1193	1178	Naphthalene			1.5 ± 0.4	-	0.7 ± 0.1	-	MS, AI, ST
1206	1213	*trans*-Pulegol			-	1.4	-	-	MS, AI
1226		Dimethyl tetrasulfide			-	-	2.4 ± 2.4	-	MS
1271	1281	2-Phenyl-2-butenal			1.3 ± 0.3	10.1	0.3 ± 0.4	10.1 ± 4.4	MS, AI
1316		9-Eicosyne			0.4 ± 0.1	-	0.2 ± 0.0	-	MS
1365		2,3,5,6-Tetrathiaheptane			1.0 ± 0.7	-	4.1 ± 1.2	-	MS
1375		Indane-4-carboxaldehyde			1.8 ± 1.6	-	2.5 ± 0.4	-	MS
1383	1387	β-Cubebene			0.4 ± 0.4	-	0.3 ± 0.1	0.6 ± 0.4	MS, AI
1427	1430	β-Copaene			0.8 ± 0.4	-	0.3 ± 0.1	-	MS, AI
1531	1528	*cis*-Calamenene			-	-	0.1 ± 0.1	-	MS, AI
1990		Ethyl hexadecanoate			-	0.9	-	-	MS
2160	2160	Octadecanoic acid			-	6.0	-	-	MS, AI
		Total identified			97.6 ± 1.0	100.0	97.2 ± 1.2	93.9 ± 1.4	

[a] Arithmetic index relative to *n*-alkanes (C9-C24) on a DB-5ms column.
[b] Arithmetic index on a DB-5ms column in reference to *n*-alkanes. (Politowicz *et al.* 2018; Adams 2007; Babushok *et al.* 2011; Hang *et al.* 2012; Kim *et al.* 2020; Lan *et al.* 2017; Shen *et al.* 2006)
[c] Lf:*L. formosana*; Cb: *C. burmannii*; Qv: *Q. variabilis*; Qg: *Q. glauca.*
[d] Identification based on comparison of the mass spectrum (MS), Arithmetic index (AI) and co-injection with standard compounds (ST).

Effects of HS-SPME Extraction Temperature on the Odor-Causing Components of Fresh Shiitake Mushrooms

To simulate typical culinary preparation, the effect of heating on the volatile composition of fresh shiitake mushroom cultivated on different logs was examined at 100 °C. The results are summarized in Fig. 3, Table 2, and Fig. 4.

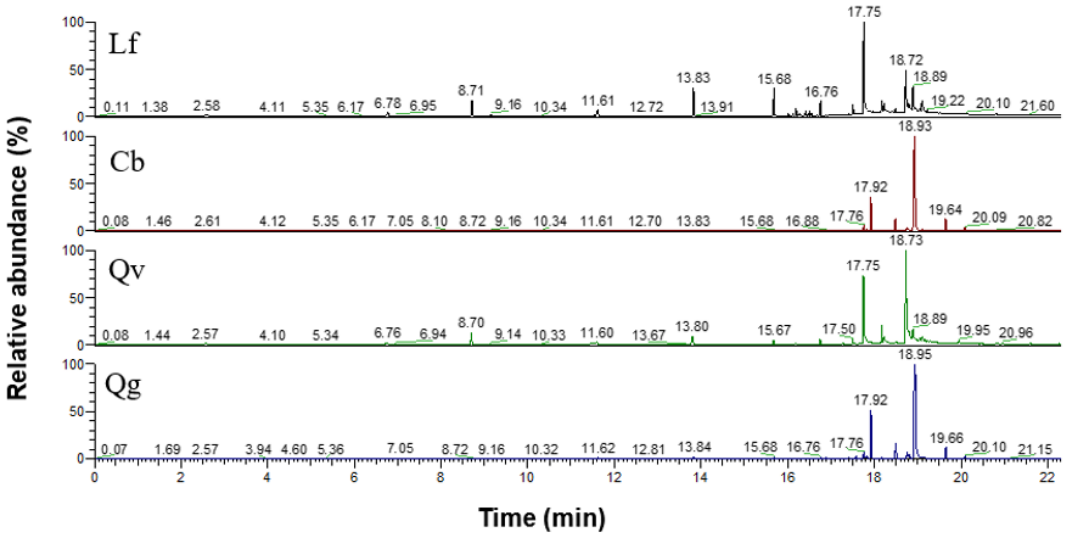

Fig. 3. Gas chromatograms of fresh *L. edodes* cultivated on four logs at high temperature (100 °C). Lf: *L. formosana*; Cb: *C. burmannii*; Qv: *Q. variabilis*; Qg: *Q. glauca*

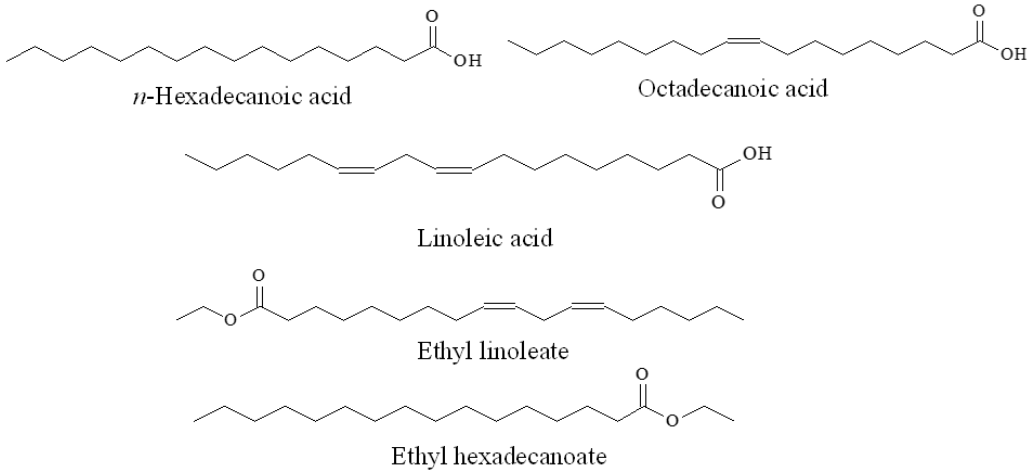

Fig. 4. Chemical structures of the primary odor-causing components of fresh *L. edodes* cultivated on four logs at high temperature (100 °C).

At high temperature, 17 compounds were identified in Lf sample, accounting for 96.4% of the total volatiles. The dominant components were *n*-hexadecanoic acid (34.5%), octadecanoic acid (27.3%), and diethylhexyl adipate (9.9%). In Cb sample, 23 compounds were detected, comprising 99.7% of the total, with ethyl linoleate (73.1%) and ethyl hexadecanoate (11.4%) as the main constituents. For Qv, 22 compounds were identified, representing 96.6% of the total volatiles, and the predominant species were linoleic acid (38.1%) and *n*-hexadecanoic acid (32.0%). In Qg, 26 compounds were detected, accounting for 99.1% of the total, with ethyl linoleate (68.0%) and ethyl hexadecanoate (13.5%) as the principal components.

Heating at 100 °C clearly shifted the volatile balance from lower molecular weight odorants toward high molecular weight fatty acids and their ethyl esters. *n*-hexadecanoic acid dominated in Lf and Qv, whereas ethyl linoleate prevailed in Cb and Qg. Conversely, *n*-hexadecanoic acid was scarce or undetected in Cb and Qg, while ethyl linoleate was absent in Lf and Qv. Several lower molecular weight volatiles, including 1-octen-3-ol, 3-

octanol, *p*-cymene, limonene, linalool, and 1,2,4-trithiolane, were detected at both temperature conditions but decreased markedly after heating. For instance, linalool decreased from 43.9 % to 4.5 % in Lf and from 24.0 % to 5.0 % in Qv, while 3-octanol decreased from 33.3 % to 0.1 % in Cb and from 32.7 % to 0.2 % in Qg (Tables 1 and 2).

Table 2. Percentages of Odor-causing Components of Fresh *L. edodes* Cultivated on Four Tree Log Types at High Temperature (100 °C)

AI[a]	rAI[b]	Compounds	Specimens				Identification[d]
			Lf[c]	Cb	Qv	Qg	
743		Carbon disulfide	2.3 ± 2.3	< 0.1	0.6 ± 0.3	< 0.1	MS
802	801	Hexanal	0.1 ± 0.1	< 0.1	0.2 ± 0.1	< 0.1	MS, AI
980	974	1-Octen-3-ol	7.7 ± 6.6	< 0.1	1.4 ± 0.1	< 0.1	MS, AI, ST
985	979	3-Octanone	1.3 ± 0.8	< 0.1	-	0.1 ± 0.1	MS, AI, ST
990	984	2-Pentylfuran	-	-	0.5 ± 0.1	< 0.1	MS, AI
997	988	3-Octanol	0.7 ± 0.5	0.1	0.1 ± 0.0	0.2 ± 0.1	MS, AI, ST
1027	1020	*p*-Cymene	1.0 ± 1.0	< 0.1	0.1 ± 0.1	< 0.1	MS, AI, ST
1032	1024	Limonene	1.6 ± 1.8	-	0.2 ± 0.0	< 0.1	MS, AI, ST
1047	1044	*trans*-Ocimene	0.5 ± 0.7	-	0.1 ± 0.0	< 0.1	MS, AI, ST
1062	1054	γ-Terpinene	0.6 ± 0.5	< 0.1	0.2 ± 0.0	< 0.1	MS, AI, ST
1100	1095	Linalool	4.5 ± 6.4	0.1	5.0 ± 0.8	< 0.1	MS, AI, ST
1106	1095	1,2,4-Trithiolane	1.0 ± 0.3	< 0.1	0.6 ± 0.1	< 0.1	MS, AI
1193	1178	Naphthalene	-	< 0.1	0.1 ± 0.0	-	MS, AI, ST
1207	1213	*trans*-Pulegol	-	-	0.1 ± 0.0	< 0.1	MS, AI
1375		Indane-4-carboxaldehyde	-	< 0.1	0.2 ± 0.1	< 0.1	MS
1383	1387	β-Cubebene	-	-	-	< 0.1	MS, AI
1528	1522	δ-Cadinene	0.5 ± 0.4	-	-	-	MS, AI
1531	1528	*cis*-Calamenene	-	-	0.2 ± 0.0	-	MS, AI
1670	1674	Hexathiepane	-	< 0.1	-	< 0.1	MS, AI
1686		Oleyl alcohol	3.0 ± 3.0	-	1.4 ± 1.2	-	MS
1734	1728	2,6-Diisopropylnaphthalene	-	-	1.4 ± 1.9	-	MS, AI
1795	1790	Tetradecanoic acid, ethyl ester	-	0.3	-	0.4 ± 0.0	MS, AI
1892		Ethyl pentadecanoate	-	0.4	-	-	MS
1925	1929	Hexadecanoic acid, methyl ester	-	0.5	-	0.7 ± 0.1	MS, AI1
1961	1961	*n*-Hexadecanoic acid	34.5 ± 23.0	-	32.0 ± 4.3	2.2 ± 0.4	MS, AI
1994	2000	Ethyl hexadecanoate	-	11.4	-	13.5 ± 1.1	MS, AI
2098	2098	Methyl linoleate	-	4.7	-	5.4 ± 0.4	MS, AI
2137	2135	Linoleic acid	-	1.6	38.1 ± 18.1	1.8 ± 1.0	MS, AI
2145	2139	Ethyl 9,12,15-octadecatrienoate	-	0.9	-	1.7 ± 0.4	MS, AI
2160	2160	Octadecanoic acid	27.3 ± 7.7	-	8.0 ± 2.2	-	MS, AI
2166	2164	Ethyl linoleate	-	73.1	-	68.0 ± 2.2	MS, AI
2260		Agatholic acid	-	6.6	-	4.7 ± 0.1	MS
2299	2299	Tricosane	-	-	5.2 ± 5.2	-	MS, AI
2327	2330	Eicosatrienoic acid, methyl ester	-	0.2	-	0.3 ± 0.1	MS, AI
2386	2398	Diethylhexyl adipate	9.9 ± 10.8	-	0.8 ± 0.3	-	MS, AI
		Total identified	96.4 ± 4.1	99.7	96.6 ± 1.5	99.1 ± 0.2	

[a] Arithmetic index relative to *n*-alkanes (C9-C24) on a DB-5ms column.
[b] Arithmetic index on a DB-5ms column in reference to *n*-alkanes. (Politowicz *et al.* 2018; Adams 2007; Babushok *et al.* 2011; Hang *et al.* 2012; Kim *et al.* 2020; Lan *et al.* 2017; Shen *et al.* 2006)
[c] Lf: *L. formosana*; Cb: *C. burmannii*; Qv: *Q. variabilis*; Qg: *Q. glauca.*
[d] Identification based on comparison of the mass spectrum (MS), Arithmetic index (AI) and co-injection with standard compounds (ST).

These results should be interpreted as changes in the headspace volatile profile during HS-SPME extraction rather than as direct changes in the total chemical composition of mushroom tissue. For fresh mushrooms, the 100 °C extraction was conducted in sealed headspace vials; therefore, the lower relative abundance of low-molecular-weight odorants does not necessarily indicate their absolute loss from the sample. Instead, the shift may reflect temperature-dependent changes in headspace partitioning, enhanced release of less volatile lipid-derived components, and possible thermal transformation of some compounds during extraction. In particular, long-chain fatty acids and their ethyl esters may become more detectable under the heated HS-SPME condition, thereby reducing the relative percentage of C8 alcohols, ketones, and other lower-molecular-weight volatiles. This interpretation is consistent with previous reports showing that thermal treatment can involve lipid oxidation, ester-related transformations, and degradation of sulfur-containing precursors in mushrooms (Zhang *et al.* 2010; Zhou *et al.* 2020; Xie *et al.* 2024). Overall, both log species and HS-SPME extraction temperature jointly shape the detected headspace volatile profiles.

Odor-Causing Components of Dried Shiitake Mushrooms under Heated HS-SPME Conditions

To simulate the hot preparation of dried shiitake mushrooms, dried mushroom powders cultivated on different logs were analyzed only at 100 °C during HS-SPME extraction. Ambient-temperature HS-SPME trials of dried samples produced signals that were too weak for reliable profiling and therefore were not included in the final results. Accordingly, the following results describe the headspace volatile profiles of dried mushrooms under a heated HS-SPME condition, rather than the effect of drying alone. The results are summarized in Fig. 5 and Table 3.

At high temperature, 14 compounds were identified in the dried Lf sample, accounting for 96.1% of the total volatiles. The dominant odor-causing components were linoleic acid (37.4%) and *n*-hexadecanoic acid (29.7%). In the dried mushrooms cultivated on Cb, 10 compounds were identified (97.3% of the total), with linoleic acid (55.7%) and *n*-hexadecanoic acid (34.9%) as the major constituents. For Qv, 13 compounds were detected (92.9%), dominated by linoleic acid (48.2%) and *n*-hexadecanoic acid (29.6%). In Qg, eight compounds were identified (99.1%), with linoleic acid (46.6%) and *n*-hexadecanoic acid (38.9%) as the principal volatiles. These findings indicate that linoleic acid and *n*-hexadecanoic acid are the predominant odor-causing components released from dried shiitake mushrooms cultivated on Cb, Qv, and Qg logs, while those grown on Lf primarily emit linoleic acid under heating.

Figure 6 compares the odor-causing components released at 100 °C from dried and fresh shiitake mushrooms cultivated on the four log species. Several consistent trends were observed. First, for Lf and Qv, the relative percentage of *n*-hexadecanoic acid was higher in fresh mushrooms than in dried ones. In contrast, mushrooms cultivated on Cb and Qg showed higher proportions of *n*-hexadecanoic acid after drying. Second, the proportion of linoleic acid increased markedly in all dried mushrooms compared to their fresh counterparts; notably, linoleic acid was undetectable in fresh Lf samples but became a major component after drying. Third, octadecanoic acid content decreased in dried Lf mushrooms but increased in the dried Cb, Qv, and Qg samples. Finally, ethyl linoleate appeared only in the fresh Cb and Qg samples and was absent in all dried mushrooms.

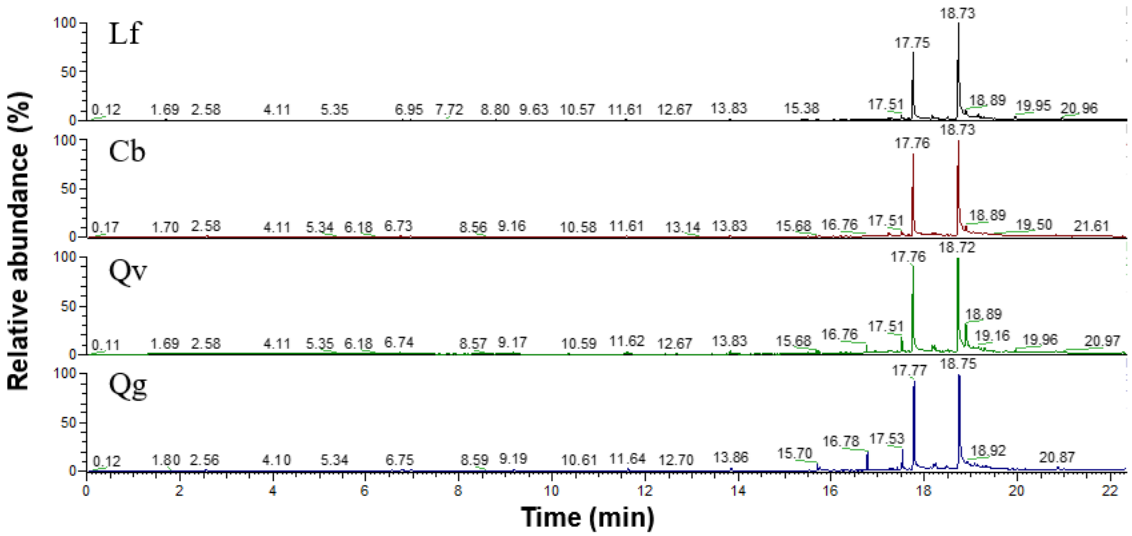

Fig. 5. Gas chromatograms of dried *L. edodes* cultivated on various tree species at high temperature (100°C). *Lf: L. formosana; Cb: C. burmannii; Qv: Q. variabilis; Qg: Q. glauca*

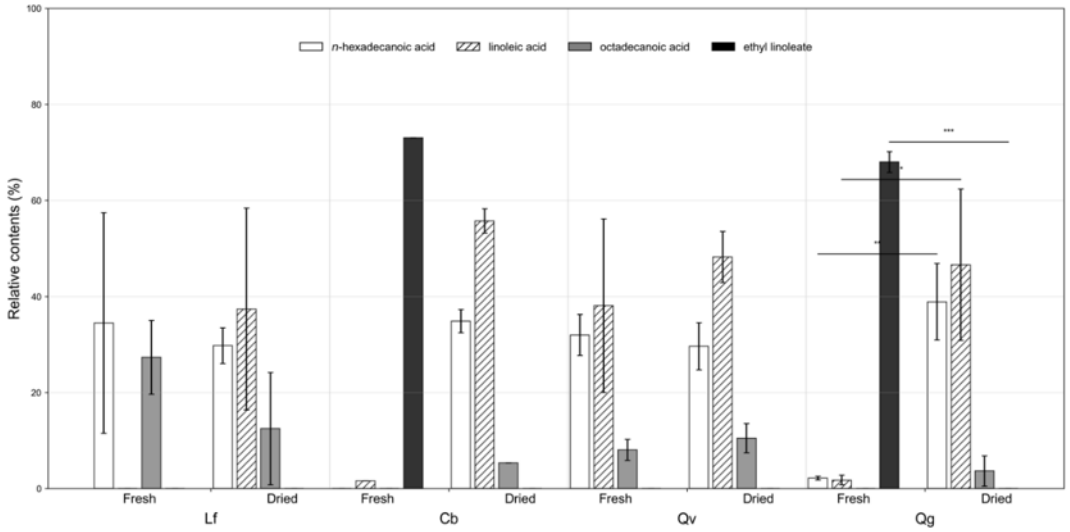

Fig. 6. Comparison of the primary odor-causing components of fresh versus dried *L. edodes* cultivated on various tree species at high temperature (100°C). Lf: *L. formosana;* Cb: *C. burmannii;* Qv: *Q. variabilis;* Qg: *Q. glauca*. Significance levels indicated as * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$)

Table 3. Percentages of Odor-causing Components of Dried *L. edodes* Cultivated on Four Tree Log Types at High Temperature (100 °C)

AI [a]	rAI [b]	Compounds	Specimens				Identification [d]
			Lf [c]	Cb	Qv	Qg	
743		Carbon disulfide	0.8 ± 0.5	-	0.3 ± 0.3	-	MS
990	984	2-Pentylfuran	0.6 ± 0.5	0.4 ± 0.1	0.5 ± 0.1	1.8 ± 2.1	MS, AI
1036	1026	1,8-Cineole	0.1 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	-	MS, AI, ST
1047	1044	*trans*-Ocimene	0.1 ± 0.1	-	-	-	MS, AI, ST
1061	1054	γ-Terpinene	0.2 ± 0.1	-	-	-	MS, AI, ST
1106	1095	1,2,4-Trithiolane	0.3 ± 0.1	0.1 ± 0.0	0.2 ± 0.1	-	MS, AI
1206	1213	*trans*-Pulegol	-	0.1 ± 0.0	-	1.4 ± 2.2	MS, AI
1226		Dimethyl tetrasulfide	-	0.1 ± 0.0	0.1 ± 0.0	1.0 ± 1.5	MS
1531	1528	*cis*-Calamenene	0.1 ± 0.1	-	0.1 ± 0.0	-	MS, AI
1628	1618	*epi*-Cedrol	0.4 ± 0.4	0.5 ± 0.1	1.0 ± 0.4	2.2 ± 1.3	MS, AI
1670	1674	Hexathiepane	-	0.2 ± 0.0	0.3 ± 0.1	1.3 ± 1.5	MS, AI
1686		Oleyl alcohol	0.8 ± 0.6	-	0.7 ± 0.2	-	MS
1961	1961	*n*-Hexadecanoic acid	29.7 ± 3.7	34.9 ± 2.4	29.6 ± 4.9	38.9 ± 8.0	MS, AI
2137	2135	Linoleic acid	37.4 ± 21.0	55.7 ± 2.5	48.2 ± 5.3	46.6 ± 15.8	MS, AI
2160	2160	Octadecanoic acid	12.5 ± 11.7	5.3 ± 0.0	10.5 ± 3.0	3.6 ± 3.2	MS, AI
2299	2299	Tricosane	1.8 ± 0.9	-	1.3 ± 0.6	-	MS, AI
2386	2398	Diethylhexyl adipate	4.0 ± 4.5	-	-	-	MS, AI
		Total identified	96.1 ± 1.0	97.3 ± 0.5	92.9 ± 1.2	96.8 ± 4.4	

[a] Arithmetic index relative to *n*-alkanes (C9-C24) on a DB-5ms column.
[b] Arithmetic index on a DB-5ms column in reference to *n*-alkanes. ((Politowicz *et al.* 2018; Adams 2007; Babushok *et al.* 2011; Hang *et al.* 2012; Kim *et al.* 2020; Lan *et al.* 2017; Shen *et al.* 2006)[c] Lf: *L. formosana*; Cb: *C. burmannii*; Qv: *Q. variabilis*; Qg: *Q. glauca.*
[d] Identification based on comparison of the mass spectrum (MS), Arithmetic index (AI) and co-injection with standard compounds (ST).

Overall, fatty acids were the predominant odor-causing compounds in both fresh and dried shiitake mushrooms under high-temperature HS-SPME conditions. Compared with fresh samples analyzed at 100 °C, dried samples showed a more consistent dominance of linoleic acid and *n*-hexadecanoic acid across log species. This pattern may be partly related to volatilization or loss of some lower-molecular-weight odorants during the multi-stage drying process, which included temperatures above room temperature. It may also reflect the enhanced detection of long-chain fatty acids during subsequent heated HS-SPME extraction. In addition, lipid-related transformations during drying and heating may contribute to the accumulation or formation of fatty-acid-derived components. However, because dried samples were not analyzed at ambient temperature, the separate effects of drying alone and heated HS-SPME extraction could not be fully distinguished. Such compositional shifts are consistent with previous reports that thermal processing can alter fatty-acid-derived volatiles and contribute to oily or fatty aroma impressions in cooked mushrooms (Xie *et al.* 2024).

Literature-Based Odor Interpretation

To contextualize the chemical results, the odor characteristics of the major volatile compounds identified in this study were interpreted based on previously reported sensory descriptions and established odor databases (Mosciano *et al.* 1995, 1998; Szumny *et al.* 2010; Elsharif *et al.* 2015; Xiao *et al.* 2016; Fan *et al.* 2017; Politowicz *et al.* 2018; The Good Scent Company 2021; Zhang *et al.* 2021).

For example, linalool is commonly described as having lavender and citrus notes, 3-octanol as mushroom and nutty, and 3-octanone as mushroom-like with cheese or moldy nuances. Dimethyl disulfide and dimethyl trisulfide contribute sulfurous and onion-like odors, whereas 1-octen-3-ol imparts herbal and earthy mushroom characteristics. Other identified volatiles, including limonene (citrus-like), camphor (camphoraceous), and long-chain fatty acids (oily or buttery), also align with established sensory profiles. By integrating these references with compositional patterns observed in the present study, qualitative odor tendencies can be inferred.

Based on the reported odor descriptors of individual compounds and the relative compositional patterns observed in this study, possible odor tendencies were inferred qualitatively. At ambient temperature, mushrooms cultivated on *L. formosana* were likely associated with lavender-, citrus-, and mushroom-like notes, because of the relatively high abundance of linalool, limonene, and 1-octen-3-ol. Mushrooms from *C. burmannii* may show stronger mushroom and nutty characteristics, mainly corresponding to 3-octanol, 1-octen-3-ol, and 3-octanone. Samples from *Q. variabilis* may have additional sulfurous attributes associated with dimethyl disulfide and dimethyl trisulfide, whereas *Q. glauca* may be characterized primarily by mushroom-like C8 alcohols and ketones.

Upon heating, fatty acid derived compounds became more prominent, suggesting a possible shift toward fatty, waxy, oily, or buttery odor impressions. In dried mushrooms from all log species, linoleic acid and *n*-hexadecanoic acid predominated, which may correspond to a generally fatty or slightly oily odor tendency based on published odor descriptors. It should be emphasized that this section provides qualitative, literature-based interpretations only. No direct sensory evaluation, trained-panel assessment, or odor activity value (OAV/ROAV) calculation was conducted in this study. Therefore, the odor tendencies discussed here should not be interpreted as confirmed sensory perceptions or quantitative aroma contributions. Nonetheless, these associations provide a preliminary sensory framework for linking volatile composition, temperature treatment, and potential aroma impressions of shiitake mushrooms cultivated on different log species. Future studies should combine HS-SPME/GC-MS analysis with OAV/ROAV calculation and standardized sensory evaluation to validate the sensory relevance of these volatile compounds.

Table 4. Sensory Description of Odor-causing Components of Shiitake Mushroom

No.	Compounds	Sensory Descriptor	References
1	Dimethyl disulfide	Sulfurous, Onion, Cabbage, Putrid	Fan *et al.* 2017
2	Hexanal	Fatty, Green, Grass, Cucumber	Politowicz *et al.* 2018; Zhang *et al.* 2021
3	*α*-Pinene	Fresh, Camphor, Sweet, Pine, Earthy, Woody	Mosciano *et al.* 1995; Szumny *et al.* 2010
4	Dimethyl trisulfide	Sulfurous, Cooked onion, Fish, Cabbage	Mosciano *et al.* 1995; Fan *et al.* 2017
5	1-Octen-3-ol	Mushroom, Earthy, Green, Oily, Fungal, Raw chicken, Cheese, Creamy, Fishy, Meaty, Herbaceous	Mosciano *et al.* 1995; Politowicz *et al.* 2018
6	3-Octanone	Musty, Mushroom, Cheese, Vegetable, Green, Berry	Politowicz *et al.* 2018
7	3-Octanol	Earthy, Nutty, Mushroom, Herbal, Melon, Citrus, Woody, Spicy, Minty	Mosciano, 1998
8	*p*-Cymene	Fresh, Citrus, Terpene, Woody, Spice	Mosciano, 1998; Politowicz *et al.* 2018
9	Limonene	Lemon, Orange, Sweet	Politowicz *et al.* 2018
10	1,8-Cineole	Citrus, Herbaceous, Fruity, Sweet, Vanilla, Minty, Pepper, Spicy, Woody	Szumny *et al.* 2010
11	Linalool	Citrus, Lavender, Floral, Sweet, Bois de rose, Woody, Green, Blueberry	Mosciano *et al.* 1995; Elsharif *et al.* 2015
12	Camphor	Strong mothball-like odor	Politowicz *et al.* 2018
13	Borneol	Camphor-like odour	Xiao *et al.* 2016
14	Naphthalene	Tar, Camphor	Zhang *et al.* 2021
15	Dimethyl tetrasulfide	Garlic, Meaty, Cabbage, Sulfur	Mosciano *et al.* 1995; Fan *et al.* 2017
16	2-Phenyl-2-butenal	Musty, Floral, Honey, Powdery, Cocoa	Mosciano *et al.* 1995
17	β-Cubebene	Citrus, Fruity	Xiao *et al.* 2016
18	Tetradecanoic acid, ethyl ester	Sweet, Waxy	Mosciano *et al.* 1995
19	*n*-Hexadecanoic acid	Waxy, Fatty	The Good Scent Company 2021
20	Ethyl hexadecanoate	Waxy, Fruity, Creamy, Milky	Mosciano 1998
21	Methyl linoleate	Oily, Fatty, Woody	The Good Scent Company 2021
22	Linoleic acid	Faint, Fatty	The Good Scent Company 2021
23	Ethyl linoleate	Mild, Fatty, Fruity, Oily	The Good Scent Company 2021

CONCLUSIONS

1. The composition of odor-causing components in shiitake mushrooms varied among log species. Linalool was dominant in mushrooms cultivated on *L. formosana* and *Q. variabilis*, whereas 3-octanol predominated in those grown on *C. burmannii* and *Q. glauca*.
2. Heating shifted the detected headspace volatile profiles from lower-molecular-weight alcohols and ketones toward long-chain fatty acids and esters such as *n*-hexadecanoic acid, linoleic acid, and ethyl linoleate. This shift may reflect temperature-dependent headspace partitioning, enhanced thermal release of less volatile lipid-derived components, and lipid-related transformations. For dried samples, prior drying may also have contributed to the volatilization or loss of some lower-molecular-weight odorants.
3. In dried mushrooms, linoleic acid and *n*-hexadecanoic acid remained predominant, likely reflecting oxidative concentration and compositional stabilization during dehydration.
4. Both log type and temperature jointly influenced the distribution of odor-causing components in shiitake mushrooms. These effects may be associated with differences in wood extractives and thermally induced lipid-related and sulfur-related transformations. The findings provide chemical insights into how cultivation materials and thermal conditions shape the potential aroma characteristics of log-grown shiitake mushrooms.

ACKNOWLEDGMENTS

The authors express special thanks to the Experimental Forest of National Taiwan University for providing the materials.

Conflicts of Interest

The authors have no conflicts of interest to declare.

REFERENCES CITED

Adams, R. P. (2007). *Identification of Essential Oil Components by Gas Chromatography-Mass Spectrometry*, 4th Ed., Allured Publishing, Carol Stream, IL, USA.

Al-Dhubiab, B. E. (2012). "Pharmaceutical applications and phytochemical profile of *Cinnamomum burmannii*," *Pharmacognosy Reviews* 6 (12), 125-131. https://doi.org/10.4103/0973-7847.99946

Babushok, V., Linstrom, P., and Zenkevich, I. (2011). "Retention indices for frequently reported compounds of plant essential oils," *Journal of Physical and Chemical Reference Data* 40, article 043101. https://doi.org/10.1063/1.3653552

Burlacu, E., Nișca, A., and Tănase, C. (2020). "A comprehensive review of phytochemistry and biological activities of *Quercus* species," *Forests* 11(9), article 904. https://doi.org/10.3390/f11090904

Chiou, C. R., and Tsao, S. H. (2017). "New thoughts on leasing land for afforestation: Mushrooms and under-forest economy," *Forest Research Newsletter* 24, 1-5. (in Chinese).

Elsharif, S. A., Banerjee, A., and Buettner, A. (2015). "Structure-odor relationships of linalool, linalyl acetate and their corresponding oxygenated derivatives," *Frontiers in Chemistry* 3, article 163755. https://doi.org/10.3389/fchem.2015.00057

Fan, Y., Yin, L., Xue, Y., Li, Z., Hou, H., and Xue, C. (2017). "Analyzing the flavor compounds in Chinese traditional fermented shrimp pastes by HS-SPME-GC-MS and electronic nose," *Journal of Ocean University of China* 16, 311-318. https://doi.org/10.1007/s11802-017-3194-y

Guo, Q., Adelina, N. M., Hu, J., Zhang, L., and Zhao, Y. (2022). "Comparative analysis of volatile profiles in four pine mushrooms using HS-SPME/GC-MS and E-nose," *Food Control* 134, article 108711. https://doi.org/10.1016/j.foodcont.2021.108711

Hang, M. Q., Zou, Q. Q., Tian, H. Y., Sun, B. G., and Chen, H. T. (2012). "Analysis of volatile components from *Dictyophora rubrovolota* Zang, Ji et Liou," *Procedia Engineering* 37, 240-249. https://doi.org/10.1016/j.proeng.2012.04.234

Hu, D., Wang, Y., Kong, F., Wang, D., Hu, C., Yang, X., Chen, X., Chen, W., and Feng, Z. (2024). "Analysis of volatile aroma components in different parts of shiitake mushroom (*Lentinus edodes*) treated with ultraviolet C light-emitting diodes based on gas chromatography-ion mobility spectroscopy," *Molecules* 29(8), article 1872. https://doi.org/10.3390/molecules29081872

Huang, S. G., Hsieh, J. C., and Sun, C. C. (1990). "Evaluation of shiitake production and quality from various hardwood log species," *Bulletin of Taiwan Forestry Research Institute* 5, 25-36. (in Chinese).

Huang, S. G., Shieh, J. C., Sun, C. C., and Cheng, S. (1988). "Wood of different fast-growing tree species on shiitake production and quality (I)," *Bulletin of Taiwan Forestry Research Institute* 3, 183-194. (in Chinese).

Kim, B. R., Kim, H. M., Jin, C. H., Kang, S. Y., Kim, J. B., Jeon, Y. G., Park, K. Y., Lee, I. S., and Han, A. R. (2020). "Composition and antioxidant activities of volatile organic compounds in radiation-bred Coreopsis cultivars," *Plants* 9, article 717. https://doi.org/10.3390/plants9060717

Lagalante, A. F., and Montgomery, M. E. (2003). "Analysis of terpenoids from hemlock (*Tsuga*) species by solid-phase microextraction/gas chromatography/ion-trap mass spectrometry," *Journal of Agricultural and Food Chemistry* 51, 2115-2120. https://doi.org/10.1021/jf021028s.

Lan, W., Lin, S., Li, X., Zhang, Q., and Qin, W. (2017). "Chemical composition of the leaf and stem essential oil of *Adenophorae radix*," *AIP Conference Proceedings* 1820, article 030001. https://doi.org/10.1063/1.4977258

Li, W., Wang, J., Chen, W., Yang, Y., Zhang, J., Feng, J., Yu, H., and Li, Q. (2019). "Analysis of volatile compounds of *Lentinula edodes* grown in different culture substrate formulations," *Food Research International* 125, article 108517. https://doi.org/10.1016/j.foodres.2019.108517

Lu, X., Hou, H., Fang, D., Hu, Q., Chen, J., and Zhao, L. (2022). "Identification and characterization of volatile compounds in *Lentinula edodes* during vacuum freeze-drying," *Journal of Food Biochemistry* 46(6), article e13814. https://doi.org/10.1111/jfbc.13814

Lu, Y. S. (2017). "Tree species and the production of shiitake mushrooms on logs," *Forest Research Newsletter* 24, 6-8 (in Chinese).

Morales, D., Tejedor-Calvo, E., Jurado-Chivato, N., Polo, G., Tabernero, M., Ruiz-Rodriguez, A., Largo, C., and Soler-Rivas, C. (2019). "In *vitro* and in *vivo* testing of the hypocholesterolemic activity of ergosterol- and β-glucan-enriched extracts obtained from shiitake mushrooms (*Lentinula edodes*)," *Food & Function* 10, 7325-7332. https://doi.org/10.1039/C9FO01744E

Mosciano, G. (1998). "Organoleptic characteristics of flavor materials," *Perfumer & Flavorist* 23, 33-35.

Mosciano, G., Fasano, M., Cassidy, J., Connelly, K., Mazeiko, P., Montenegro, A., Allen, B. B., Michalski, J., and Sadural, S. (1995). "Organoleptic characteristics of flavor materials," *Perfumer & Flavorist* 20, 31-33.

Orban, A., Jerschow, J. J., Birk, F., Suarez, C., Schnell, S., and Rühl, M. (2023). "Effect of bacterial volatiles on the mycelial growth of mushrooms," *Microbiological Research* 266, article 127250. https://doi.org/10.1016/j.micres.2022.127250

Ouyang, X., Yi, S., Lu, H., Wu, S., and Zhao, H. (2016). "*Liquidambar formosana* Hance: A mini-review of chemical constituents and pharmacology," *European Journal of Medicinal Plants* 17(1), 1-11. https://doi.org/10.9734/EJMP/2016/29440

Piska, K., Sulkowska-Ziaja, K., and Muszynsk, B. (2017). "Edible mushroom *Pleurotus ostreatus* (oyster mushroom): Its dietary significance and biological activity," *Acta Scientiarum Polonorum Hortorum Cultus* 16, 151-161.

Politowicz, J., Lech, K., Lipan, L., Figiel, A., and Carbonell-Barrachina, A. (2018). "Volatile composition and sensory profile of shiitake mushrooms as affected by drying method," *Journal of the Science of Food and Agriculture* 98, 1511-1521. https://doi.org/10.1002/jsfa.8622

Shen, X., Gao, Y., and Su, Q. (2006). "Constituents of the essential oil of *Rhizoma polygonati*," *Flavour and Fragrance Journal* 21, 556-558. https://doi.org/10.1002/ffj.1666

Szumny, A., Figiel, A., Gutiérrez-Ortíz, A., and Carbonell-Barrachina, Á. A. (2010). "Composition of rosemary essential oil (*Rosmarinus officinalis*) as affected by drying method," *Journal of Food Engineering* 97, 253-260. https://doi.org/10.1016/j.jfoodeng.2009.10.019

The Good Scent Company. (2021). "Flavor ingredients," available at: (http://www.thegoodscentscompany.com/).

Tisdale, T. E., Miyasaka, S. C., and Hemmes, D. E. (2006). "Cultivation of the oyster mushroom (*Pleurotus ostreatus*) on wood substrates in Hawaii," *World Journal of Microbiology and Biotechnology* 22, 201-206. https://doi.org/10.1007/s11274-005-9020-5

Xiao, Z., Fan, B., Niu, Y., Wu, M., Liu, J., and Ma, S. (2016). "Characterization of odor-active compounds of various *Chrysanthemum* essential oils by gas chromatography-olfactometry, gas chromatography-mass spectrometry and their correlation with sensory attributes," *Journal of Chromatography B* 1009-1010, 152-162. https://doi.org/10.1016/j.jchromb.2015.12.029

Xie, L., Guo, S., Rao, H., Lan, B., Zheng, B., and Zhang, N. (2024). "Characterization of volatile flavor compounds and aroma-active components in button mushroom (*Agaricus bisporus*) across various cooking methods," *Foods* 13(5), article 685. https://doi.org/10.3390/foods13050685

Zhang, J. J., Li, Y., Zhou, T., Xu, D. P., Zhang, P., Li, S., and Li, H. B. (2016). "Bioactivities and health benefits of mushrooms mainly from China," *Molecules* 21, 938-953. https://doi.org/10.3390/molecules21070938

Zhang, S. X., Xie, J. C., and Sun, B. G. (2010). "Analysis of volatile flavors in *Lentinus edodes* by solid-phase microextraction combining with GC-MS," *Journal of Beijing Technology and Business University (Natural Science Edition)* 28, 1-5, 13.

Zhang, W., Lao, F., Bi, S., Pan, X., Pang, X., Hu, X., Liao, X., and Wu, J. (2021). "Insights into the major odor-active compounds in clear red raspberry juice (*Rubus idaeus* L. cv. Heritage) by molecular sensory science approaches," *Food Chemistry* 336, article 127721. https://doi.org/10.1016/j.foodchem.2020.127721

Zhou, T. Y., Liu, H., Wu, Q. Q., Hao, L., Pan, D. D., and Dang, Y. L. (2020). "The flavor quality of dried *Lentinus edodes* with different species and drying methods (charcoal roasting and natural drying)," *Journal of Food Measurement and Characterization* 14, 613-622. https://doi.org/10.1007/s11694-020-00377-5

Article submitted: December 16, 2025; Peer review completed: April 17, 2026; Revisions accepted: May 18, 2026; Published: May 27, 2026.
DOI: 10.15376/biores.21.3.6398-6415