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Decoding the aroma of Jägermeister liqueur through sensory-directed flavor analysis combined with solvent-assisted flavor evaporation and headspace-stir bar sorptive extraction

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ABSTRACT

Jägermeister liqueur is one of the most famous herbal liqueurs worldwide, distinguished by its unique anise-like, bitter, and caramel-like flavor. This study comprehensively analyzed its aroma components using sensory-directed flavor analysis combined with gas chromatography-mass spectrometry and gas chromatography-sulfur chemiluminescence detector. Results identified eugenol (clove-like, OAV = 1260), anethole (anise-like, OAV = 723), *p*-anisaldehyde (almond-like, OAV = 97), linalool (flowery, OAV = 25), and terpinen-4-ol (apple-like, OAV = 119) as key aroma-active compounds in Jägermeister. Two sulfur-containing compounds with meaty and caramel-like aromas were detected; however, their OAVs were below 1. Ethers (53.2 mg/L), phenolics (27.8 mg/L), and terpenoids (10.5 mg/L) were the most abundant compounds in Jägermeister, while esters were present at relatively low concentrations (254 μg/L). A comparative analysis revealed that Jägermeister exhibits a unique aroma profile among ten European herbal liqueurs, particularly enriched in caramel-like and licorice-like notes, which showed positive correlations with key aroma compounds such as vanillin. This work not only provides the first systematic aroma deconstruction of Jägermeister, but also offers new insights into the compositional patterns and classification of European herbal liqueurs, contributing to quality control, product authentication, and flavor optimization.

1. Introduction

Herbal liqueurs, traditionally consumed as aperitifs or digestives, form a significant and distinctive segment within the liqueur family (Montero, Schmitz, & Meckelmann, 2020). Active in the global beverage market, these liqueurs are often savored on their own or in cocktails (Solmonson, 2024). Among them, Jägermeister stands out as Germany's most renowned herbal liqueur brand. Jägermeister is characterized by its anise-like, bitter, caramel-like, citrus, floral, fruity, herbaceous, hot, minty, sweetish, thick, and warm spicy flavor (Lahne et al., 2018). Jägermeister is produced using a process that combines 56 different herbs, blossoms, roots, and fruits from various regions. These ingredients undergo maceration in stainless steel tanks with distilled alcohol to extract their flavors. As a critical step in flavor development, maceration determines the types and concentrations of the extracted compounds. Excessive maceration may lead to the over-oxidation of liqueur and extraction of undesirable compounds, which could negatively impact the sensory quality of the final product (Sun et al., 2018). Following maceration, the resulting liquid is then filtered and aged in oak barrels for at least one year, allowing the flavors to blend and mature. After aging, the liquid is blended with sugar, caramel, water, and alcohol, followed by another round of filtration before bottling,

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ensuring consistency in the final product (Śliwińska et al., 2015).

Although herbal liqueurs represent a unique and culturally significant category within spirits, systematic studies on their aroma profiles remain scarce. Most existing research has focused on identifying volatile compounds using various analytical techniques, often without evaluating their sensory relevance (Śliwińska et al., 2015). For instance, Petrović et al. (2021) applied headspace-gas chromatography-mass spectrometry (GC-MS) to detect 29 odor compounds, reporting menthone, eucalyptol, and menthol as dominant monoterpenoids based on abundance. Similarly, Rodríguez-Solana et al. (2021) and Rosa et al. (2023) identified terpenoids—such as menthone, isomenthone, α-thujene, limonene, 1,8-cineole, and linalool—as major odor compounds in pennyroyal and myrtle liqueurs using GC-FID/MS (gas chromatography-flame ionization detector/MS), based on their relatively high concentrations. However, these conclusions were based solely on chemical data, without confirming whether these compounds actually contribute to the perceived aroma.

In contrast, a few studies have incorporated sensory relevance into their analysis (Śliwińska et al., 2015; Lahne et al., 2018). Rodríguez-Solana et al. (2016), for example, employed liquid-liquid extraction (LLE) combined with GC-FID and GC-MS to identify 32 odor compounds in 28 herbal liqueurs. Among these, ethyl octanoate, eugenol, ethyl hexanoate, eucalyptol, and thymol were highlighted as key odorants based on their odor activity values (OAVs)—defined as the ratio of a compound's concentration to its odor threshold, which estimates its potential contribution to aroma perception. However, given that only a small portion of odor compounds in food contribute to the overall flavor, there has been a noticeable lack of research on the sensory-directed flavor analysis of herbal liqueurs (Lin et al., 2024; Mahmoud & Zhang, 2024). This gap highlights the need for a detailed investigation into the aroma-active compounds of herbal liqueurs.

Moreover, as an alcoholic product of maceration, the composition of Jägermeister liqueur could be very complex, containing compounds with low to high boiling points. Previous studies have shown that headspace or distilled flavor trapping techniques can largely influence the components of aroma extracts (Starowicz, 2021; Wang, Yang, et al., 2022; Zhang et al., 2023). Distilled flavor trapping techniques, such as solvent-assisted flavor evaporation (SAFE), are prone to extract more high-boiling, less-volatile aromatic compounds in the matrix such as anethole and eugenol (Engel et al., 1999; Jeleń et al., 2012). On the other hand, headspace techniques, such as headspace-stir bar sorptive extraction (HSSE), mainly retain low-boiling, highly volatile components through van der Waals forces and hydrogen bonds, which may be lost during distilled flavor extraction (Granvogl & Schieberle, 2022). In some cases, both headspace and matrix components are crucial to the overall aroma of foods (Ma et al., 2020; Wang, Li, et al., 2022). Therefore, to ensure a comprehensive and reliable characterization of Jägermeister's aroma, both SAFE and HSSE are employed to capture a broad spectrum of volatile compounds. In addition, although sulfur-containing compounds such as 1-hexanethiol, dimethyl trisulfide, methional, 3-methyl-3-sulfanyl butanol, and 3-sulfanylheptanal have been reported as key aroma contributors in wine and baijiu (Wang et al., 2017; Liu & Sun, 2018), such compounds have rarely been reported in herbal liqueurs. Given their low odor thresholds and high sensory impact, trace-level sulfur volatiles may still play an important role in overall aroma perception. Therefore, in addition to GC-MS analysis, gas chromatography-sulfur chemiluminescence detector (GC-SCD) was employed to enable selective identification, and quantification of sulfur-containing compounds potentially present in Jägermeister.

This study uses Jägermeister as a representative herbal liqueur and aims to: i) characterize the key aroma-active compounds of Jägermeister using SAFE and HSSE, along with sensory-directed flavor analysis methods such as aroma extract dilution analysis (AEDA) and OAV calculations; ii) investigate the aroma compound composition of nine other herbal liqueurs by first combining SAFE and GC-MS analysis to identify volatile compounds, followed by multivariate statistical analyses, including principal component analysis (PCA) and Spearman correlation analysis, to identify common patterns and differences. Studying the flavor of liqueurs helps monitor the production process, optimize flavor and aroma, and verify the authenticity and origin of the product (Śliwińska et al., 2015).

2. Materials and methods

2.1. Sample

Mast-Jägermeister SE (Wolfenbüttel, Germany) kindly provided the Jägermeister liqueur sample, which contains 35 % alcohol by volume (*v/v*) and 13 % sugar by weight (*w/w*).

In addition, nine other commercial herbal liqueurs were included in this study to provide contextual reference for interpreting the aroma profile of Jägermeister. These products were selected based on their classification as herbal liqueurs, a category traditionally produced using maceration of complex botanical mixtures. While the exact formulations are proprietary, they share similar production principles and serve as representative products within the same market segment.

The comparative samples were purchased from the Kaufland supermarket in Stuttgart, Germany, and included: Fernet-Branca (Milan, Italy; 35 % alcohol), Kümmerling (Bodenheim, Germany; 27 % alcohol), Amaro Averna (Sicily, Italy; 29 % alcohol), Ramazzotti Amaro 1815 (Milan, Italy; 30 % alcohol), Rimano Amaro (Neckarsulm, Germany; 30 % alcohol), Wilthener (Nörten-Hardenberg, Germany; 30 % alcohol), Alpenkräuter Gurktaler (Vienna, Austria; 27 % alcohol), Jagdgeselle (Goch, Germany; 35 % alcohol), and Becherovka (Karlovy Vary, Czech Republic; 38 % alcohol).

2.2. Chemicals

Aroma standard chemicals were commercially purchased: diacetyl (99 %), geranyl acetate (98 %), benzothiazole (97 %), *p*-anisaldehyde (98 %), and *δ*-decalactone (97 %) were purchased from Alfa Aesar (Kandel, Germany); camphene (≥95 %), limonene (95 %), isoamyl alcohol (98.5 %), *α*-terpineol (60 %), anethole (99 %), (*E*)-cinnamaldehyde (98 %), eugenol (99 %), vanillin (99 %), and linalool (99 %) were obtained from Carl Roth (Karlsruhe, Germany); estragole (97 %), octanal (99 %), 2-acetyl-2-thiazoline (96 %), geraniol (98 %), terpinen-4-ol (95 %), isoeugenol (97 %), 1-octen-3-one (96 %), 1,2-dichlorobenzene (99 %), and 2-phenylethanol (95 %) were purchased from Sigma-Aldrich (Taufkirchen, Germany); eucalyptol (99 %), ethyl butanoate (99 %), 3-hydroxy-2-methyl-4*H*-pyran-4-one (99 %), decanal (96 %), citral (95 %), 2-methyl-5-(methylthio)furan (99 %), 5-methylfurfural (98 %), and ethyl hexanoate (99 %) were purchased from Thermo Fischer Scientific (Massachusetts, USA); 3-mercapto-2-methyl-1-pentanol (97 %) and bis(2-methyl-3-furyl) disulfide (98 %) were obtained from TCI (Tokyo, Japan); methyl eugenol (98 %), eugenol (95 %), and ethyl 3-methylbutanoate (99 %) were obtained from J&K (California, USA); and propyl heptanoate (97 %) was purchased from BLD Pharma (Reinbek Germany).

Sodium chloride (>99.0 %), anhydrous sodium sulfate (>99.0 %), dichloromethane (99.9 %), and ethanol (99.7 %) were obtained from Th. Geyer (Renningen, Germany). Table sucrose was purchased from the REWE supermarket (Stuttgart, Germany).

2.3. Aroma extraction methods

SAFE. The Jägermeister sample (60 mL) was first diluted to 20 % alcohol by volume (*v/v*) (Willner et al., 2013) and mixed with internal standards: 200 μL 1,2-dichlorobenzene (200 mg/L) and 200 μL thymol (200 mg/L). The mixture was then thoroughly extracted three times with 60 mL of dichloromethane each time. The combined organic phases were washed with saturated brine, and the extract was dried over anhydrous sodium sulfate. The SAFE technique removed the nonvolatile

material. Then the extract was concentrated to a final volume of approximately 500 μL using a Vigreux column (50 × 1 cm i.d.) followed by microdistillation. Other liqueurs were subjected to the same SAFE procedure to obtain the corresponding aroma extractions.

HSSE. To avoid the loss of highly volatile odorants, HSSE was additionally used to capture volatile compounds. Jägermeister liqueur was first diluted to 10 % alcohol by volume (*v/v*) to reduce the adsorption of ethanol on the polydimethylsiloxane coating of the twister. Then, the 10 mL diluted sample was placed in a 20 mL headspace glass vial and spiked with internal standards (20.18 μL of 200 mg/L 1,2-dichlorobenzene) and 3.5 g of sodium chloride. A 10 mm stir bar with 0.5 mm polydimethylsiloxane (Gerstel, Mülheim an der Ruhr, Germany) was placed in the headspace of the glass vial (20 mL) and stirred at 700 rpm. The extraction time was 60 min and the extraction temperature was at room temperature (20 ± 1 °C). The TDU parameters were the same as described by Stöppelmann et al. (2023).

2.4. AEDA combined with SAFE

The SAFE extracts of Jägermeister liqueur were stepwise diluted using dichloromethane in a ratio of $1:3^n$ ($0 \leq n \leq 8$), and then injected into the injection port of GC-MS-olfactometry (O) from small to high dilution folds until no odors could be perceived. The highest dilution folds where an odor was still detected were considered as the flavor dilution (FD) factors.

2.5. Aroma dilution analysis (ADA) combined with HSSE

For HSSE extracts of Jägermeister liqueur, revised ADAs were performed by increasing the split ratios (Rigling et al., 2019). After the normal HSSE extraction process, the aroma-loaded stir bar was placed at the injected port and desorbed at split ratios of $1:2^n$ ($0 \leq n \leq 10$). The dilution continued until no odor could be detected. The highest split ratio was considered as the FD factor.

2.6. GC-MS-O analysis

The parameters of GC-MS-O were the same as described by Stöppelmann et al. (2023). A gas chromatograph (7890B, Agilent Technologies, Inc., Santa Clara) connected to a mass spectrometry detector (5977B, Agilent Technologies, Inc., Santa Clara) and an olfactometry detection port (ODP 4, Gerstel) were applied to conduct the AEDA, ADA, identification and quantification analysis. A DB-WAX column or a nonpolar DB-5 column (both 30 m × 0.25 mm i.d., 0.25 μm film thickness, Agilent Technologies, Inc.) was equipped to the GC to separate the odorants. The DB-WAX column was used during the whole process, including AEDA, identification and quantification. DB-5 column was soley used for the calculation of retention indices (RIs) for identification of the target compounds. Helium (99.999 %) was used as the carrier gas, with a constant flow rate of 1.62 mL/min. The oven program of the GC was set as follows: initial temperature, 40 °C; hold for 3 min; increased to 240 °C with a speed of 5 °C/min; hold for 10 min. Full scan mode (*m/z* 40–330) was used. The temperatures of the ion source and quadrupole were 230 °C and 150 °C, respectively. The electron ionization energy was set at 70 eV. The temperatures of the ODP 4 transfer line and mixing chamber were 250 °C and 150 °C, respectively. Each sniffing was repeated three times by two experienced panelists.

2.7. GC-SCD

SCD was used to specifically detect the sulfur-containing compounds in Jägermeister liqueur. The GC-SCD system consisted of an Agilent 7890B GC connected to an SCD 355 detector with a DB-WAX column installed. The GC parameters were the same as those used in GC-MS. For the Agilent 355 SCD, the base temperature was held at 280 °C, and the temperature of the dual plasma controller was set at 800 °C. The hydrogen and air flow rates were set at 40 mL/min and 5 mL/min, respectively.

2.8. Identification of aroma compounds

For GC-MS analysis, odor-active compounds extracted by both SAFE and HSSE were identified using three criteria: (1) interpretation of their mass spectra; (2) comparison of their RIs on both polar and nonpolar columns with those of authentic standards; and (3) verification of their odor attributes through olfactometry detection using authentic standards at similar concentrations. For GC-SCD analysis, compounds were identified by comparing their RIs and retention times with those of authentic standards, as well as with RI values from literature sources such as the NIST database (https://webbook.nist.gov/chemistry/) and Flavornet (http://flavornet.org). In both cases, a compound was considered positively identified based on RI if the difference between its experimental RI and the reference RI was within ±30.

2.9. Quantitative analysis

2.9.1. Quantification of SAFE extracts using GC-MS

1,2-Dichlorobenzene and thymol were used as internal standards based on their structural similarity, polarity, and retention time relative to the target compounds. Calibration solutions were prepared by mixing the analytes and internal standards in dichloromethane at eight concentration ratios: 1:100, 1:50, 1:20, 1:5, 1:2, 1:1, 2:1, and 5:2. These concentration ratios were selected to ensure that the peak areas of most compounds fell between 10^4 and 10^7. Each calibration solution and the SAFE distillate (extracted as per section 2.3) were injected (2 μL) into the GC-MS. Calibration curves were generated by plotting the ratio of the target compound to the internal standard concentrations (*x*-axis) against their respective peak area ratios (*y*-axis). The recovery rates of the quantified odorants were determined using a model liqueur matrix consisting of 35 % ethanol and 10 % sucrose, and calculated as the ratio of the quantified results to the actual concentration (Table S1). All analyses were performed in triplicate to ensure reproducibility.

2.9.2. Quantification of sulfur compounds using SAFE combined with GC-SCD

Two sulfur-containing compounds, 2-methyl-5-(methylthio)furan and benzothiazole, were quantified using methyl propyl disulfide (50 μg/L) as the internal standard. Methyl propyl disulfide was chosen due to its similar volatility, ensuring accurate quantification of benzothiazole and 2-methyl-5-(methylthio)furan. As in section 2.9.1, 2 μL of each calibration solution and the SAFE distillate of Jägermeiter liqueur were injected into the GC-MS. The calibration levels and recovery rates were measured following the same method described in section 2.9.1 (Table S1). All measurements were performed in triplicate.

2.9.3. Quantification of HSSE extracts using GC-MS

1,2-Dichlorobenzene was selected as the internal standard for the target compounds identified using HSSE because it has similar polarity to the target compounds. Calibration solutions were prepared by mixing the analytes and internal standards in concentration ratios of 1:50, 1:20, 1:5, 1:2, 1:1, 2:1, and 5:1. To simulate the matrix effects, the calibration solutions were prepared in a matrix containing 10 % ethanol and saturated with 3.5 g NaCl. HSSE extraction procedure was performed as described in section 2.3 to ensure method consistency. Recovery tests for HSSE were performed in the same matrix and calculated as the ratio of the quantified results to the actual concentration (Table S1). Each sample was analyzed in triplicate.

2.10. Sensory analysis

2.10.1. Sensory panel

Sensory analysis—including odor threshold determination, aroma profile analysis, as well as recombination and omission tests—were conducted in an odorless lab maintained at 20 ± 1 °C. The sensory panel for odor threshold determination consisted of 10 members (aged 24–33) recruited from the Department of Flavor Chemistry of the University of Hohenheim, all with extensive experience in sensory analysis. Throughout the experiments, the sample temperature was maintained at 20 °C. Both reference samples and Jägermeister liqueur (10 mL) were presented in odorless glass bottles (retention indices () with aluminum caps. During the aroma profiling of Jägermeister, the samples were not anonymized. However, in the recombination and omission tests, all samples were anonymized and labeled with three-digit codes.

2.10.2. Odor threshold determination

The odor thresholds of four odorants, estragole, 2-methyl-5-(methylthio)furan, benzothiazole, and methyl eugenol were measured using a matrix consisting of 35 % ethanol and 10 % sucrose, as their odor thresholds in such a system have not been previously reported in the literature. The 10-sample test was used to determine the odor thresholds (Zhu et al., 2023). Each test set included a labeled blank, a reference sample, and 8 test samples. The test samples included two unknown blanks and six samples with varying concentrations, each increasing by a factor of three. Panelists were asked to identify and record what they perceived as different from the blank. The threshold data were processed with the curve fitting method, where a curve was plotted with logarithmic concentration (*x*-axis) and the probability of detection (*y*-axis). The detection threshold was defined as the concentration at which the probability of detection reached 50 % (Picard et al., 2015).

2.10.3. Aroma profile analysis

Before the aroma profile analysis, two training sessions were conducted. In the first session, panelists were asked to propose odor descriptors for Jägermeister, with communication allowed. The 11 descriptors with the highest frequency of mention were selected for use in the subsequent sessions. In the second session, panelists were trained to evaluate the odor intensities of references solutions, with the references for the 11 descriptors were: alcoholic (35 % ethanol), sweetish (vanillin), fruity (ethyl 3-methylbutanoate), flowery (2-phenyl ethanol), pine-like (estragole), anise-like (anethole), licorice-like (licorice candy), cinnamon-like (*E*-cinnamaldehyde), citrus-like (limonene), caramel-like (caramel solution), and minty (mint leaves). Except for ethanol, licorice candy, caramel solution, and mint leaves, all odorants were prepared at 100 times their odor threshold. After training, panelists were able to correctly identify the reference odors with a score variance of less than 20 % inter-individual variance. Each panelist evaluated the sample once, and the averaged scores were used in the final analysis.

2.10.4. Recombination and omission tests

To closely replicate the Jägermeister liqueur, a 35 % ethanol solution mixed with 10 % sucrose was used as the matrix of recombinates. The aroma recombination model was prepared by adding the selected odorants, with OAVs >1 and FD factors ≥27, to the matrix at their actual concentrations as found in Jägermeister (the specific components are listed in Table S2). Then the aroma profile analysis of this recombinate was conducted using the same descriptors, intensity scale, and reference standards as in section 2.10.3.

For omission tests, seven omission models were prepared, each excluding a odorant group. Triangle tests were applied to explore the significance of omitting groups, in which each set consisted of one omitted model and two aroma recombination models. Panelists were instructed to identify the sample with a different aroma and report the corresponding three-digit code.

2.11. Data processing

Calibration curves, mean values, standard deviations of the quantitative analysis, as well as paired t-test compairing the aroma profiles of Jägermeister and its recombinates, were performed using Excel 2019 (Microsoft, USA). The *p* values for the omission tests were computed using the binomial distribution in R 4.4.0 (R Core Team, 2024) (Vienna, Austria). Data visualization, PCA anaysis, ANOVA and correlation analysis were conducted using R, RStudio, and OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA). The heatmap was visualized using Python 3.10 (Python Software Foundation, Delaware, USA) with columns normalized.

3. Results and discussion

3.1. Aroma profile analysis of Jägermeister

Aroma profile analysis was carried out to give a first impression of overall aroma of Jägermeister liqueur. These descriptors were selected by the sensory panel to summarize the aroma profile of Jägermeister liqueur: anise-like, sweetish, licorice-like, alcoholic, cinnamon-like, pine-like, caramel-like, minty, citrus-like, fruity, and flowery. The most intense attributes in Jägermeister liqueur were sweetish (1.9), followed by alcoholic (1.8), licorice-like (1.8), caramel-like (1.7), fruity (1.3), anise-like (1.6), cinnamon-like (0.7), minty (0.8), pine-like (0.8), flowery (0.6), and citrus-like (0.6) (Fig. 1a). This description was mostly consistent with the previous reports (Lahne et al., 2018).

3.2. Screening and identification of key odorants in Jägermeister

In SAFE distillate of Jägermeister liqueur, 28 odorous regions were detected by GC-MS-O, with FD factors ranging from 3 to 6561 (Table 1, Fig. S1a). The highest FD factor of 6561 was perceived for anise-like (**17**), floral (**18**), cinnamon-like (**22**), clove-like (**24**), and sweetish (**28**) odors. Then followed by a second high FD factor of 2187, perceived as chicken-like (**9**), green (**10**), flowery (**11**), and anise-like (**21**) odor notes. Citrus (**15**) and milk-like (**20**) notes achieved an FD factor of 81. Moreover, odor impressions with lower FD factors were determined for bread (**4**), citrus (**5, 27**), fusel (**6**), bitter (**8**), and flowery (**16**) (Table 1 and Fig. 2).

For identification of the key odorants, their mass spectrums, RIs on both DB-WAX and DB-5MS, and odor notes were detected and compared with authentic reference chemicals. By this way, the odorants with the highest FD factors of 6561 in SAFE distillates were identified as anethole (**17**; anise-like), geraniol (**18**; floral), (*E*)-cinnamaldehyde (**22**; cinnamon-like), eugenol (**24**; clove-like), and vanillin (**28**; sweetish). Odorants with the second-highest FD factors of 2187 included 2-methyl-5-(methylthio)furan (**9**; chicken-like), (*E*)-2-octenal (**10**; green), linalool (**11**; flowery), *p*-anisaldehyde (**21**; anise-like). Other key aromas with lower FD factors were shown in Table 1. Notably, some volatile compounds showed high FD factors but were not detected by MS. For example, 2-methyl-5-(methylthio)furan (FD = 2187) shows no signal in the chromatogram obtained by MS, but has a clear signal on the chromatogram obtained by SCD detector, which exclusively detects sulfur-containing compounds.

As a supplement to SAFE-screened aroma-active compounds, HSSE-ADA enabled the identification of eight odorants with moderate to high volatility: ethyl butanoate (HS-1; fruity), ethyl 3-methylbutanoate (HS-2; fruity), eucalyptol (HS-3; pine-like), ethyl hexoate (HS-4; fruity), decanal (HS-5; citrus-like), terpinen-4-ol (HS-6; pine-like), methyl eugenol (HS-7; pine-like), and benzothiazole (HS-8; caramel-like) (Table 2, Fig. S1b). Among them, eucalyptol exhibited the highest FD factor of 512, followed by ethyl 3-methylbutanoate and benzothiazole, with FD factors of 128 and 64, respectively. Ethyl butanoate, ethyl hexoate, decanal, terpinen-4-ol and methyl eugenol had FD factors below 8 but OAV values greater than 1, indicating their potential

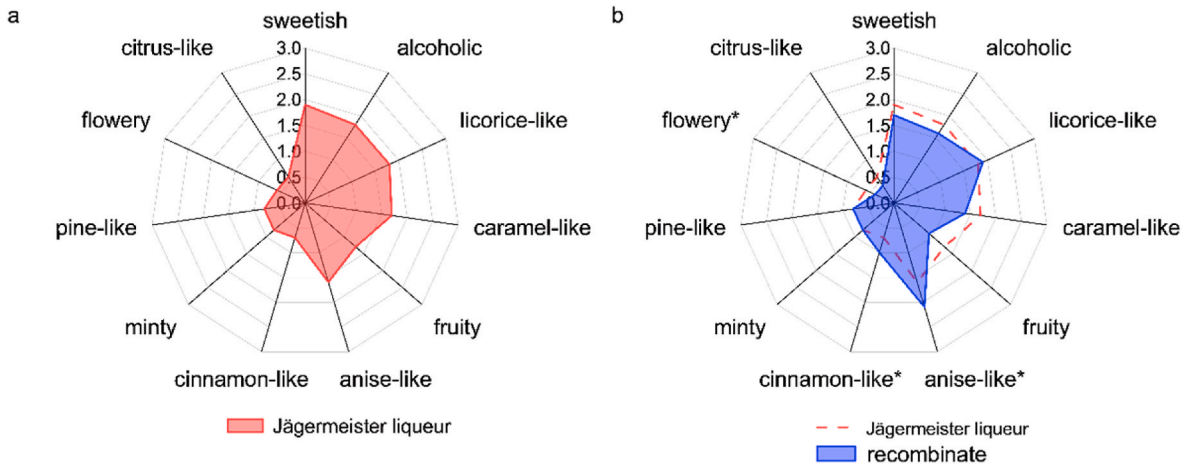

Fig. 1. Aroma profiles of Jägermeister liqueur and its recombinate.

Table 1
Odorous regions of the GC-MS-O analysis and identification results in SAFE distillates of Jägermeister.

no.[a]	odorant	CAS	odor quality[b]	RI (DB-WAX)		RI (DB-5)		FD[d]	odor intensity[e]	identification method[f]
				measured	ref.[c]	measured	ref.[c]			
1	2,3-butanedione	431-03-8	yogurt-like	993	991			3	3	RI, odor, S
2	2-methyl-3-buten-2-ol	115-18-4	fruity, flowery	1058	1036			9	2	MS, RI, odor
3	camphene	79-92-5	woody	1078	1057			9	2	MS, RI, odor, S
4	3-penten-2-ol	1569-50-2	bread-like	1179	1174			27	2	MS, RI, odor
5	limonene	138-86-3	citrus	1206	1203			27	2	MS, RI, odor, S
6	isoamyl alcohol	123-51-3	fusel, alcoholic	1214	1211	730	732	27	2	MS, RI, odor, S
7	eucalyptol	470-82-6	pine-like, citrus	1219	1211			3	3	MS, RI, odor
8	octanal	124-13-0	bitter, citrus	1294	1297	1004	1001	27	2	MS, RI, odor, S
9	2-methyl-5-(methylthio)furan	13678-59-6	chicken-like	1372	1352			2187	2	RI, odor, S, SCD
10	(*E*)-2-octenal	2548-87-0	green	1393	1416			2187	1	RI, odor
11	linalool	78-70-6	flowery	1554	1549	1098	1099	2187	3	MS, RI, odor, S
12	terpinen-4-ol	562-74-3	apple-like	1613	1601	1186	1177	3	2	MS, RI, odor
13	safranal	116-26-7	nutty, sweetish	1657	1648			3	2	MS, RI, odor
14	estragole	140-67-0	sweetish, spicy	1677	1655	1201	1195	3	2	MS, RI, odor, S
15	*α*-terpineol	98-55-5	pine-like	1707	1692	1198	1192	81	4	MS, RI, odor, S
16	geranyl acetate	105-87-3	flowery, fruity	1764	1756			27	3	RI, odor, S
17	anethole	104-46-1	anise-like	1842	1819	1298	1289	6561	4	MS, RI, odor, S
18	geraniol	106-24-1	floral	1855	1849			6561	3	MS, RI, odor, S
19	2-phenylethanol	60-12-8	flowery	1917	1912			3	3	MS, RI, odor, S
20	*γ*-nonalactone	104-61-0	milk-like	1979	1993			81	3	RI, odor
21	*p*-anisaldehyde	123-11-5	anise-like	2035	2011	1267	1277	2187	3	MS, RI, odor, S
22	(*E*)-cinnamaldehyde	104-55-2	cinnamon-like	2043	2033			6561	4	MS, RI, odor, S
23	zingiberenol	58334-55-7	lemon-like	2106	2104			3	3	RI, odor
24	eugenol	97-53-0	clove-like	2172	2167	1362	1356	6561	4	MS, RI, odor, S
25	unknown		star anise-like	2200				3	4	odor
26	*δ*-decalactone	705-86-2	coconut-like	2241	2221			3	3	RI, odor, S
27	isoeugenol	97-54-1	citrus	2302	2330			27	3	RI, odor, S
28	vanillin	121-33-5	sweetish	2567	2566			6561	4	MS, RI, odor, S

[a] Numbered according to the RIs of odorants on the DB-WAX column. Each compound has an exclusive no. in this article.
[b] Odor quality of each odorant at the sniffing port during the GC-O.
[c] The reference RIs were from NIST database (https://webbook.nist.gov/chemistry/) or Flavornet (http://flavornet.org).
[d] Flavor dilution factors determined on DB-WAX column during AEDA.
[e] Odor intensity from GC-O analysis was scored from 0 to 5. The final intensity was determined by the most frequently observed value across experiments.
[f] Identification based on MS (mass spectrum), RI (retention index), odor description, S (standard compounds), or SCD (SCD detector).

contributions to the overall aroma (Fig. 2).

3.3. Quantitative analysis of Jägermeister

A total of twenty-five aroma compounds were quantified using calibration curves with corresponding internal standards (Table S1), and their concentrations are presented in Table 3. AEDA was initially used to identify the key aroma compounds in Jägermeister liqueur. However, AEDA based screening may overlook the impact of the matrix on aroma release (Wang, Li, et al., 2022). To address this limitation, additional aroma compounds with lower FD factors were also quantified. The three most abundant aroma compounds in Jägermeister liqueur were anethole (52.8 mg/L), eugenol (26.4 mg/L), and limonene (6.5 mg/L). Other major volatiles detected at concentrations above 500 μg/L included vanillin (2.8 mg/L), *p*-anisaldehyde (2.0 mg/L), *α*-terpineol (1.9 mg/L), isoeugenol (967 μg/L), eucalyptol (662 μg/L), isoamyl alcohol (644 μg/L), terpinen-4-ol (596 μg/L), decanal (587 μg/L), and linalool (563 μg/L). In contrast, methyl eugenol (452 μg/L), estragole (401 μg/L), (*E*)-cinnamaldehyde (284 μg/L), geraniol (144 μg/L) and ethyl butanoate (126 μg/L) were present at concentrations above 100 μg/L. Additionally, two sulfur-containing aroma compounds, benzothiazole (0.529 μg/L) and 2-methyl-5-(methylthio)furan (0.002 μg/L), were

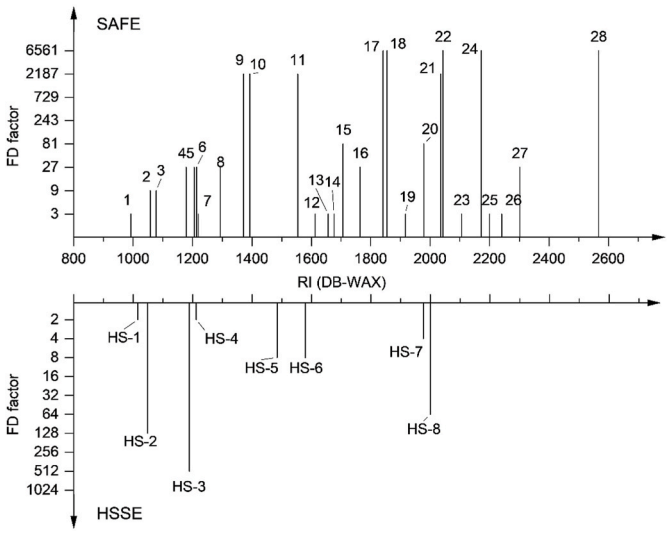

Fig. 2. Aroma extract dilution analysis-based flavor dilution chromatograms of Jägermeister from solvent-assisted flavor evaporation (SAFE) and headspace-stir bar sorptive extraction (HSSE) extracts (peak numbering corresponds to Tables 1 and 2).

detected at trace levels.

Among the chemical classes of volatiles, ethers were found to be the most abundant, with a total concentration of 53.2 mg/L (Fig. 3a). Anethole (52.8 mg/L) was the dominant contributor, whereas estragole (401 μg/L) contributed to a less extent. Both anethole and estragole are major constituents of fennel, which contains 66.1 % estragole and 1.5 % anethole (Rodríguez-Solanam et al., 2014). Phenolic compounds were the second most abundant class, with a total concentration of 27.8 mg/L, primarily contributed by eugenol (26.4 mg/L). Eugenol imparts a spicy, clove-like aroma and is the major volatile component in clove buds (Eugenia caryophyllus). It is also found in nutmeg and cinnamon (Zachariah & Leela, 2006). Furthermore, eugenol was identified as a dominant compound in green walnut liqueur, a traditional beverage produced from unripe walnuts macerated in alcohol with added sugar and spices (Petrović et al., 2021).

Terpenoids represented the most diverse class of aroma-active compounds in Jägermeister, with 11 individual species identified (Fig. 3b–Table S3) and a total concentration of 10.5 mg/L (Fig. 3a). In contrast, only three esters were detected, totaling 254 μg/L. This trend—high abundance of terpenoids and the low abundance of esters—is consistent with previous studies on herbal liqueurs produced via ethanol-based maceration (Petrović et al., 2019; Rodríguez-Solana et al., 2021; Rosa et al., 2023). The dominance of terpenoids is largely attributed to the botanical nature of the raw materials, which are readily extracted by ethanol during maceration. On the other hand, esters—especially short-chain ethyl esters—are biosysthesized primarily during fermentation and are less characteristic of non-fermented products like Jägermeister.

For example, Petrović et al. (2019) found that monoterpenes were the most abundant volatile compounds in herbal bitter liqueurs, based on GC peak area percentages. The main constituents included menthone (3.75 %), eucalyptol (3.42 %), and menthol (3.10 %), whereas esters were detected at much lower levels—for example, ethyl acetate at 0.58 % and methyl acetate at 0.20 %. Similarly, Rodríguez-Solana et al. (2021) reported that monoterpenes in pennyroyal liqueur accounted for 81.00–92.93 % of total volatiles in laboratory-scale samples and 27.24–100 % in commercial products, while esters contributed only 9.58 %.

In contrast, Li et al. (2023) reported that Semillon liqueur exhibited a markedly different volatile composition, dominated by esters (45.45 %), followed by alcohols (25.00 %), aldehydes (13.64 %), ketones (6.82 %), acids (4.55 %), and olefins/others (2.27 % each). Key esters included ethyl acetate, isoamyl acetate, ethyl caproate, and ethyl caprylate.

From a sensory perspective, terpenoids such as menthone, 1,8-cineole, and linalool contribute cooling, herbal, minty, and floral notes (Table 1), which are key to the identity of traditional herbal liqueurs (Lahna et al., 2018). The relatively low ester content may explain the muted fruity or sweet nuances, distinguishing Jägermeister from fruit-based or wine-based liqueurs, in which esters dominate the aroma profile.

These findings emphasiye the influence of both raw material composition and extraction method on the final aroma profile. Understanding these compositional features is critical not only for product characterization but also for guiding formulation stratergies. For instance, enhancing fruity esters through co-fermentation or post-maceration blending may offer new flavor dimensions if product innovation is desired. Conversely, maintaining the terpenoid-rich profile reinforces the herbal authenticitz preferred in traditional formulations.

To provide a broader perspective on the aroma characteristics of Jägermeister, nine additional European herbal liqueurs were selected for comparison. These products share maceration as a key production method to extract the flavor components in botanicals. We investigated the concentrations of sixteen volatile compounds in nine additional herbal liqueurs produced in Germany (Kümmerling, Rimano Amaro, Wilthener, Jagdgeselle), Italy (Fernet-Branca, Amaro Averna, Ramazzotti Amaro 1815), Austria (Alpenkräuter Gurktaler), and the Czech Republic (Becherovka). To enable a consistent and meaningful comparison across all samples, 16 volatile compounds that were commonly detected via SAFE were selected for quantitative analysis. These compounds were consistently present in the SAFE extracts of most liqueurs and represent a range of key aroma-contributing chemical classes,

Table 2
Odorous regions of the GC-MS-O analysis and identification results of HSSE extracts of Jägermeister.

no.	odorant	CAS	odor quality[a]	RI (DB-WAX)		RI (DB-5)		FD[c]	odor intensity[d]	identification method[e]
				measured	ref.[b]	measured	ref.[b]			
HS-1	ethyl butanoate	105-54-4	fruity	1016	1044			2	2	MS, RI, odor, S
HS-2	ethyl 3-methylbutanoate	108-64-5	fruity	1049	1055	858	856	128	2	MS, RI, odor, S
HS-3	eucalyptol	470-82-6	pine-like, citrus	1189	1211			512	2	MS, RI, odor, S
HS-4	ethyl hexoate	123-66-0	fruity	1212	1227	998	1000	2	1	MS, RI, odor, S
HS-5	decanal	112-31-2	citrus, wax-like	1484	1498			8	3	MS, RI, odor, S
HS-6	terpinen-4-ol	562-74-3	apple-like	1579	1601	1186	1180	8	1	MS, RI, odor, S
HS-7	methyl eugenol	93-15-2	herbal	1976	2003	1399	1403	4	2	MS, RI, odor, S
HS-8	benzothiazole	95-16-9	caramel-like	1999	1973			64	3	RI, odor, S, SCD

[a] Odor quality of each odorant at the sniffing port during the GC-O.
[b] The reference RIs were from NIST database (https://webbook.nist.gov/chemistry/) or Flavornet (http://flavornet.org).
[c] Flavor dilution factors determined on DB-WAX column during AEDA.
[d] Odor intensity from GC-O analysis was scored from 0 to 5. The final intensity was determined by the most frequently observed value across experiments.
[e] Identification based on MS (mass spectrum), RI (retention index), odor description, S (standard compounds), or SCD (SCD detector).

Table 3
Concentrations, odor thresholds, and odor activity values (OAVs) of selected odorants in Jägermeister.

odorant	concentration (μg/L)	OT (μg/L)	OAV
eugenol	26,400 ± 3730	21.0 [c]	1260.0
anethole	52,800 ± 5660	73.0 [c]	723.0
limonene	6540 ± 585	10.0 [d]	654.0
terpinen-4-ol[a]	596 ± 93	5.0 [e]	119.0
p-anisaldehyde	2040 ± 57	21.0 [e]	97.1
methyl eugenol[a]	452 ± 17	10.1 [f]	44.7
isoeugenol	967 ± 188	23.0 [c]	42.0
eucalyptol[a]	662 ± 18	21.0 [e]	31.5
estragole	401 ± 46	16.1 [f]	24.9
linalool	563 ± 30	23.0 [g]	24.5
ethyl 3-methylbutanoate[a]	85 ± 15	7.0 [c]	12.1
ethyl hexanoate[a]	43 ± 4	5.0 [c]	8.6
decanal[a]	587 ± 31	71.0 [c]	8.3
vanillin	2820 ± 191	439 [c]	6.4
α-terpineol	1910 ± 340	400 [h]	4.8
ethyl butanoate[a]	126 ± 12	82.0 [c]	1.5
geraniol	144 ± 14	130 [h]	1.1
(*E*)-cinnamaldehyde	284 ± 54	750 [c]	<1
camphene	37 ± 5	1860 [d]	<1
octanal	38 ± 2	40.0 [c]	<1
isoamyl alcohol	644 ± 61	179000 [c]	<1
2-phenylethanol	48 ± 9	2600 [g]	<1
geranyl acetate	55 ± 4	510 [i]	<1
2-methyl-5-(methylthio)furan [b]	0.002 ± 0.001	0.069 [f]	<1
benzothiazole [b]	0.529 ± 0.041	13.5 [f]	<1

[a] These compounds were quantified using HSSE combined with GC-MS, while those without a footnote were quantified using SAFE combined with GC-MS.
[b] These compounds were identified using SAFE combined with GC-SCD.
[c] Odor thresholds obtained from the review by Liu & Sun (2018) on Chinese Baijiu.
[d] Odor thresholds determined in cocktails by Niu et al. (2020).
[e] Odor thresholds sourced from Van Gemert (2011), with matrices being 10 % ethanol (*v/v*) or similar ethanol solutions.
[f] Odor thresholds determined by our panelists using a matrix composed of 35 % (*v/v*) ethanol and 10 % sucrose.
[g] Odor thresholds determined in brandy by Willner et al. (2013).
[h] Odor thresholds determined in cognac spirits by Thibaud et al. (2020).
[i] Odor thresholds determined in 10 % (*v/v*) ethanol aqueous by Peltz (2016).

including esters, terpenoids, and phenylpropanoids. The corresponding quantitative data are provided in Supplementary Table S4.

3.4. OAV analysis of Jägermeister

OAVs provide a better indication of the relative contribution of each compound to the overall aroma (Duan et al., 2024). While FD factors indicate the relative importance of aroma compounds in the gas phase (air), OAV values consider a more complex matrix and reflect the interactions between aroma compounds and the liquid-phase environment (Wang, Li, et al., 2022). Therefore, OAV was used as an additional metric to assess the contribution degree of every compound to the overall aroma. Table 3 shows that seventeen odorants exhibited OAVs above 1. The compound with the highest OAV was eugenol (1260.0), followed by anethole (723.0), limonene (654), terpinen-4-ol (119.0), *p*-anisaldehyde (97.1), methyl eugenol (44.7), isoeugenol (42.0), eucalyptol (31.5), estragole (24.9), linalool (24.5), ethyl 3-methylbutanoate (12.1), ethyl hexanoate (8.6), decanal (8.3), vanillin (6.4), *α*-terpineol (4.8), ethyl butanoate (1.5) and geraniol (1.1). Eight odorants were considered to have negligible contributions to the overall aroma of Jägermeister liqueur since the OAVs were below 1. Notably, (*E*)-cinnamaldehyde exhibited a high FD factor (6561) but an OAV below 1, suggesting that strong matrix effects suppressed its impact in solution. Similarly, two sulfur-containing compounds had FD factors above 64 but OAVs below 1, indicating that the complex matrix of Jägermeister liqueur diminished their distinct aroma, ultimately reducing their contribution to the overall aroma perception. These discrepancies highlight the influence of different media on odor perception, reinforcing the importance of OAV analysis in fully understanding their sensory impact.

Due to the lack of matrix-specific thresholds for all compounds, literature values were used to provide a comparative reference. For four key compounds, thresholds were experimentally determined in a model solution mimicking the Jägermeister matrix.

3.5. Aroma recombination of Jägermeister

The aroma recombination analysis was conducted to replicate the overall aroma of the Jägermeister liqueur, providing direct evidence to validate the identification and quantitation data (Wang, Li, et al., 2022). The recombination model was prepared by blending selected odorants with OAVs >1 and FD factors ≥27 (Table S2). The aroma profiles of Jägermeister liqueur and the recombinate are shown in Fig. 1. The overall aroma profile similarity between the recombinate and the original Jägermeister liqueur was 82 %, calculated as the mean of the individual accuracy scores for each aroma descriptor, demonstrating a high degree of recurrence in the reconstruction of key odorants in Jägermeister liqueur (Fig. 1). In the recombination model, the most intense aroma attribute was anise-like (2.1), followed by licorice-like (1.9), sweetish (1.7), and alcoholic (1.6). Other notable attributes included caramel-like (1.4), cinnamon-like (1.0), fruity (0.9), minty (0.8), pine-like (0.8), flowery (0.4), and citrus-like (0.4) (Fig. 1b). Compared with the original liqueur, the flowery attribute in the recombinate was slightly lower (0.2 difference), while the cinnamon-like and anise-like attributes were slightly higher (0.3 and 0.5 differences, respectively) on a sensory scale from 0 to 3. Other attributes, including sweetish, alcoholic, licorice-like, caramel-like, pine-like, and minty, showed no significant differences between the recombination model and the original sample, as indicated by a paired t-test ($p > 0.05$). These findings suggest that the recombination model closely mimicked the overall aroma profile of Jägermeister liqueur, despite slight variations in specific attributes.

3.6. Omission tests of Jägermeister

To further confirm the role of individual odorants in the overall perception of Jägermeister, omission tests were performed by systematically excluding certain groups of volatile compounds from the recombination model (Wang, Li, et al., 2022). The recombination model missing specific sets of compounds were compared to the complete model and the triangle test results are shown in Table 4. The omission of six odorants with OAVs <1 ($p = 0.896$) and sulfur-containing compounds ($p = 0.896$) did not significantly alter the overall aroma perception, suggesting their minor role in the aroma profile of Jägermeister and confirming the accuracy of the OAV results. In contrast, the omission of sweetish, fruity and flowery compounds ($p = 0.020$) significantly changed the perceived aroma, highlighting their significance in overall profile. Notably, removing only fruity odorants ($p = 0.441$) did not result in a significant change, suggesting that sweetish and flowery odorants with OAV>1 (linalool, terpinen-4-ol, geraniol, eugenol, and vanillin) were the key contributors to Jägermeister's aroma profile. Moreover, fruity odorants did not significantly affect the overall aroma perception. The removal of anise-like odorants, anethole and *p*-anisaldehyde, approached statistical significance ($p = 0.077$), implying a possible, but statistically inconclusive, contribution to the overall aroma.

3.7. Comparative analysis of Jägermeister and other European herbal liqueurs

To provide a contextual information on the aroma and volatiles composition of herbal liqueurs, a comparison of aroma profiles of Jägermeister and other herbal liquers was performed (Fig. 4a and

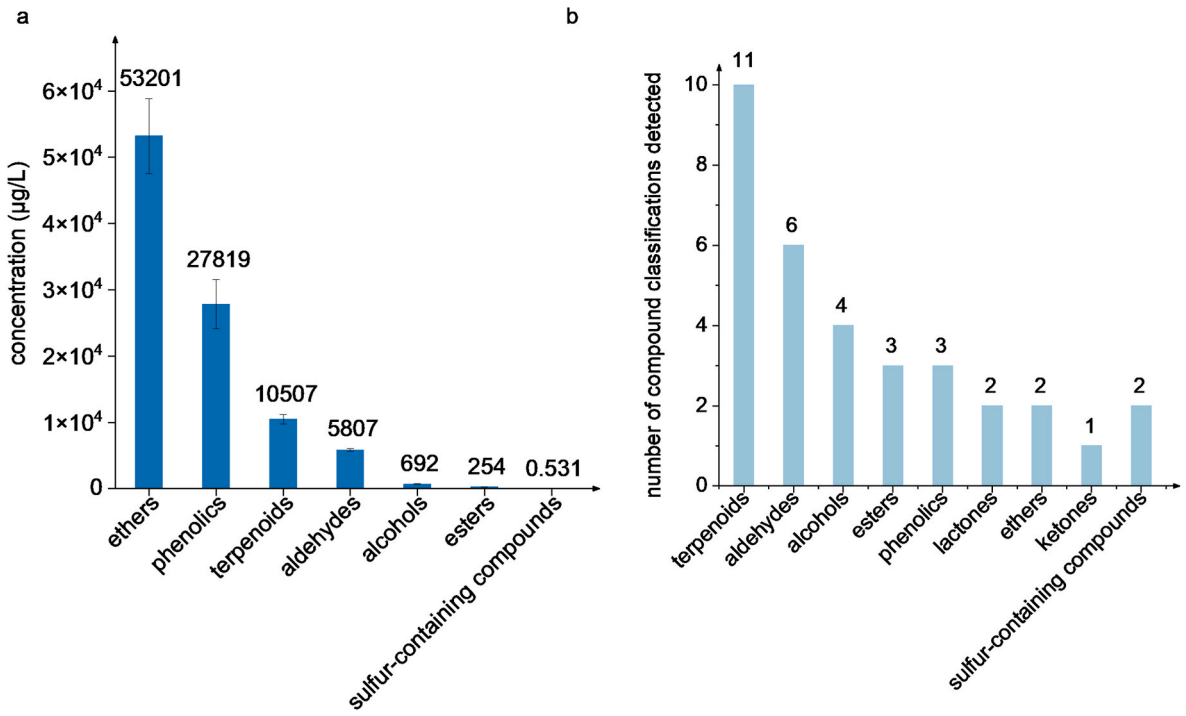

Fig. 3. Classification (a) and concentration (b) of aroma-active compounds identified in Jägermeister liqueur.

Table 4
Number of correct answers and statistical significance (p-values) in omission tests.

test	odorants omitted	correct answers	p^a
A1	aroma compounds with OAV<1 (6, 8, 9, 16, 22, HS-8)	2	0.896
A2	aroma compounds with sulfur-containing compounds (9, HS-8)	2	0.896
B1	aroma compounds with an anise-like odor (17, 21)	6	0.077
B2	aroma compounds with sweetish, fruity and flowery odor (11, 12, 16, 18, 24, 28, HS-1, HS-2, HS-4)	7	0.020
B3	aroma compounds with a fruity odor (HS-1, HS-2, HS-4)	4	0.441
B4	aroma compounds with a cinnamon-like odor (22)	4	0.441
B5	aroma compounds with a woody odor (7, 14)	5	0.215
B6	aroma compounds with citrus-like odor (5, 7, 8, 15, 27, HS-5)	4	0.441

[a] p value was calculated from the binomial test.

Fig. S2), along with the PCA analysis (Fig. 4b and c). As shown in Fig. 4a, JG exhibited higher intensitie in caramel-like, licorice-like, fruity, and sweetish notes compared to other samples. Notably, statistically significant differences ($p < 0.05$) were found in cinnamon-like ($p = 0.004$), sweetish ($p = 0.031$) and alcoholic ($p = 0.036$) attributes, as indicated by asterisks. Among the samples, BC the strongest cinnamon-like aroma (1.7), RA1815 has the strongest citrus-like aroma (1.4), BC has the highest flowery aroma, and FB the strongest minty aroma and pine-like aromas. PCA revealed that JG possessed a distinct aroma profile, as it fell outside the 95 % confidence ellipse, while other liqueurs were projected within it. The loading plot showed that caramel-like and licorice-like notes were the strongest positive contributors distinguishing JG from other liqueurs, consistent with the aroma profile results (see Fig. 4a).

Spearman correlation analysis revealed that most aroma attributes showed significant correlations with key volatiles (see Fig. 5)). For example, vanillin ($r = 0.75$) and geraniol ($r = 0.60$) positively contributed to caramel-like aroma, while octanal ($r = -0.42$) showed a negative correlation. The sweetish note was positively associated with geraniol ($r = 0.60$) and negatively with camphene ($r = -0.40$). Cinnamon-like attributes were strongly related to (*E*)-cinnamaldehyde ($r = 0.84$), while α-terpineol showed an opposing trend ($r = -0.82$), highlighting the role of independent contributors. Interestingly, anise-like aroma was positively related to camphene ($r = 0.42$) and *p*-anisaldehyde ($r = 0.16$), but slightly negatively to anethole ($r = -0.10$), which has a typical anise-like aroma. The expected positive relationship between anethole and anise-like aroma was not observed in this study. Several explanations may account for this discrepancy, including perceptual masking from coexisting volatiles, a broader sensory interpretation of "anise-like" by the panel, or limited variation in the data set. These factors may have obscured the typical role of anethole in shaping the anise-like note in herbal liqueurs.

4. Conclusion

This study analyzed the key aroma compounds in Jägermeister liqueur using sensory-directed flavor analysis combined with SAFE and HSSE extraction methods. Eugenol (clove-like), anethole (anise-like), linalool (flowery), and terpinen-4-ol (apple-like) were identified as the most important aroma-active compounds, based on their OAVs>20 and confirmed contributions through recombination and omission testing. In terms of concentration, ethers, phenolics, and terpenoids—such as anethole, eugenol and limonene—were the most abundant chemical classes. In contrast, esters such as ethyl butanoate and ethyl 3-methylbutanoate were present in lower amounts. A comparative analysis revealed Jägermeister's distinct aroma profile, characterized by stronger caramel-like and licorice-like notes, primarily associated with key volatiles such as vanillin, highlighting its sensory uniqueness among European herbal liqueurs. One limitation of this study is that it was based on a single production batch of Jägermeister. Future work should incorporate multiple batches across different time points to account for batch-to-batch and seasonal variation. These findings provide practical guidance for improving the production and quality control of herbal liqueurs. Identifying key aroma contributors and selecting effective extraction methods help ensure product consistency and sensory appeal.

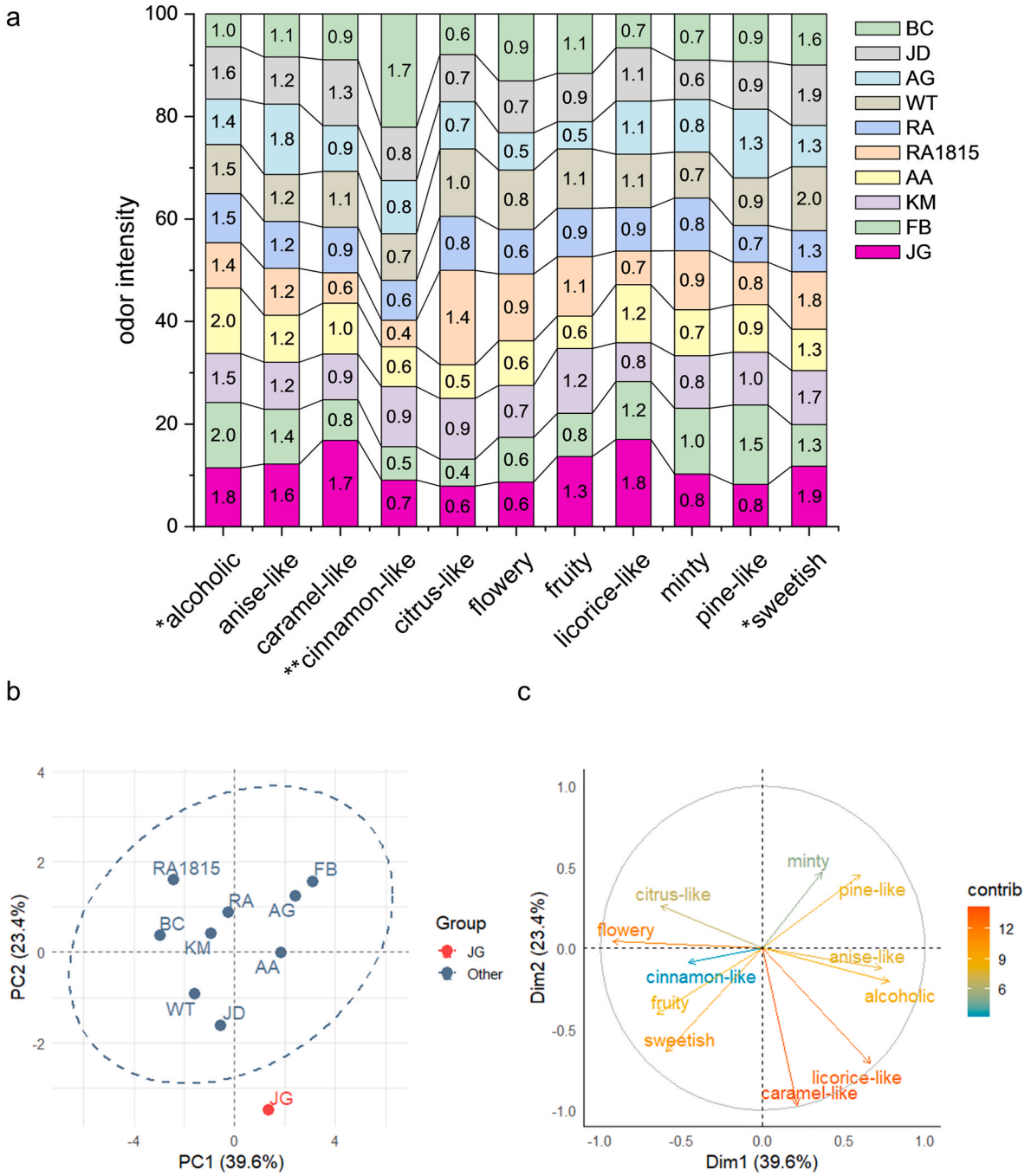

Fig. 4. Odor profile comparison among ten European herbal liqueurs and principal component analysis (PCA) of their aroma attributes. (a) Stacked bar chart of mean odor intensities across 11 descriptors; asterisks indicate significant differences between JG and other samples ($p < 0.05$); (b) PCA score plot showing sample distribution based on odor profiles; (c) PCA loading plot indicating aroma descriptor contributions.
Abbreviations: FB, Fernet-Branca (Milan, Italy); KM, Kümmerling (Bodenheim, Germany); AA, Amaro Averna (Sicily, Italy); RA1815, Ramazzotti Amaro 1815 (Milan, Italy); RA, Rimano Amaro (Neckarsulm, Germany); WT, Wilthener (Nörten-Hardenberg, Germany); AG, Alpenkräuter Gurktaler (Vienna, Austria); JD, Jagdgeselle (Goch, Germany); BC, Becherovka (Karlovy Vary, Czech Republic).

CRediT authorship contribution statement

Lin Zhu: Writing – original draft, Visualization, Investigation. **Zexin Lin:** Investigation. **Yan Zheng:** Writing – review & editing, Investigation. **Jiaqi Liang:** Visualization, Investigation. **Yupan Li:** Software, Investigation. **Sarah Kramp:** Writing – review & editing, Investigation. **Youfeng Zhang:** Writing – review & editing, Investigation. **Can Xiang:** Writing – review & editing. **Leyin Chen:** Writing – review & editing. **Marina Rigling:** Writing – review & editing. **Lea Hannemann:** Writing – review & editing. **Claudia Oellig:** Writing – review & editing. **Yanyan Zhang:** Writing – review & editing, Supervision, Conceptualization.

Ethical review

All panelists participated voluntarily and provided written consent. Ethics approval was obtained from the Ethics Committee of the Research Support Department at the University of Hohenheim (2024/26_Zhu).

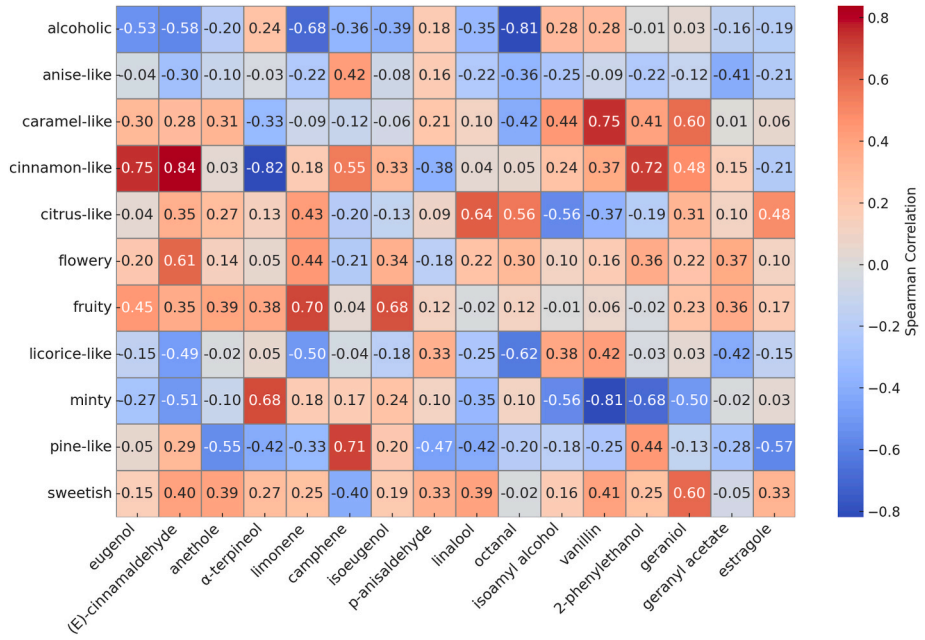

Fig. 5. Spearman correlations between aroma descriptors and volatile compound contents in ten herbal liqueurs.
Abbreviations: FB, Fernet-Branca (Milan, Italy); KM, Kümmerling (Bodenheim, Germany); AA, Amaro Averna (Sicily, Italy); RA1815, Ramazzotti Amaro 1815 (Milan, Italy); RA, Rimano Amaro (Neckarsulm, Germany); WT, Wilthener (Nörten-Hardenberg, Germany); AG, Alpenkräuter Gurktaler (Vienna, Austria); JD, Jagdgeselle (Goch, Germany); BC, Becherovka (Karlovy Vary, Czech Republic).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations used

AEDA, aroma extract dilution analysis; ADA, aroma dilution analysis; FD, flavor dilution; GC-FID, gas chromatography-flame ionization detector; GC-MS, gas chromatography-mass spectrometry; GC-MS-O, gas chromatography mass spectrometry-olfactometry; GC-SCD, gas chromatography-sulfur chemiluminescence Detector; HSSE, headspace-stir bar sorptive extraction; LLE, liquid-liquid extraction; NIST, national institute for standards and technologies; OAV, odor activity value; ODP, olfactometry detection port; OT, odor threshold; PCA, principal component analysis; RI, retention index; SAFE, solvent-assisted flavor extraction.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.118265.

Data availability

Data will be made available on request.

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