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Comparison of volatile compounds and sensory profiles of edible insect oils by HS-SPME-Arrow-GC/MS with Maillard reaction

2025

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Comparison of volatile compounds and sensory profiles of edible insect oils by HS-SPME-Arrow-GC/MS with Maillard reaction

A Master's Thesis
Submitted to the
Graduate School of Sungshin Women's University

in partial fulfillment of the requirements
for the degree of Master of Food Chemistry

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05, 2025

This is to certify that we have examined the
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ABSTRACT

Comparison of volatile compounds and sensory profiles of edible insect oils by HS-SPME-Arrow-GC/MS with Maillard reaction

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This study investigates the effects of roasting on the volatile profiles and sensory attributes of oils extracted from five edible insects. Ultrasound-assisted extraction was used to obtain oils, and optimal roasting conditions (150 ℃, 30 min, and 0.26 ×g) were identified using response surface methodology with a Box-Behnken design. Volatile compounds were analyzed using headspace solid-phase microextraction arrow combined with gas chromatography - mass spectrometry (HS-SPME-Arrow-GC/MS), with method validation showing $R^2 \geq 0.9800$, recoveries of 90.09 - 109.98 %, and the limits of detection 1.03 - 62.52 ng/g, and quantification of 3.22 - 197.38 ng/g. Roasting increased desirable Maillard-derived compounds, including 2-pentylfuran and pyrazines.

Sensory evaluation showed increased odor-liking scores after roasting, attributed to enhanced nutty, roasted, grainy, bread-like, and baked notes and suppression of sour, spoiled, fishy, and ammonia-like notes. These results suggest that roasting process improves the sensory quality of edible insect oils and supports their application in food product development.

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Ⅰ. Introduction

With the world population projected to exceed 9 billion, edible insects have emerged as a promising dietary resource for enhancing global food security (Cha et al., 2024). Insects offer several advantages over conventional livestock, including reduced land and feed requirements, lower production costs, and decreased greenhouse gas and ammonia emissions (da Silva et al., 2020; Perez-Santaescolastica et al., 2023). Nutritionally, edible insects are rich in monounsaturated and polyunsaturated fats, high-quality proteins, and essential micronutrients such as magnesium, copper, phosphorus, iron, and biotin (Otero et al., 2020; Ribeiro et al., 2024). As a result, approximately 2 billion people across more than 113 nations currently include edible insects in their diets (Nam et al., 2025). The worldwide edible insect market reached a value of USD 1.35 billion in 2024 and is expected to grow at an annual rate of 25.1 % through 2030 (da Silva et al., 2020). Despite these benefits, consumer acceptance of insect-based foods remains limited, due to neophobia, unappealing appearance, and concerns regarding food safety (Ribeiro et al., 2024). Therefore, further research is needed to improve consumer perceptions and increase the appeal of edible insect products.

Edible insect oil, in particular, has demonstrated high nutritional value owing to its abundant unsaturated fatty acids, which are known to support cardiovascular health. The fatty acid composition of insect oil is comparable to that of common vegetable oils such as peanut and rapeseed oils (Lee, Kim et al., 2023; Nam et al., 2025). Lipids constitute the second most abundant component of edible insects after proteins

(Otero et al., 2020). During protein extraction, insects are typically defatted, and the extracted lipids are often discarded. However, utilizing these lipids presents a valuable opportunity to improve resource efficiency through upcycling (Lee et al., 2022). While most current studies focus on protein extraction or processing methods (Bottle et al., 2025; Hoon Lee et al., 2024; Zhang et al., 2024), research on the sustainable utilization of insect-derived oils remains limited.

Previous studies indicate that consumers' rejection of foods containing edible insect oil is often associated with undesirable volatile compounds, such as rancid or feed-like aroma (Ribeiro et al., 2024). Consequently, roasting has been proposed as a strategy to improve the volatile profile and sensory quality of edible insect oils. Heat induced Maillard reactions generate volatile compounds such as pyrazines and furans, which impart nutty note and intensify the color (Adelina et al., 2021; Ma et al., 2024; Zhang et al., 2022).

The Maillard reaction proceeds through three stages. In the initial stage, a Schiff base is formed via the reaction between amino groups and the carbonyl group of reducing sugars (Lee, Choi et al., 2024). This intermediate subsequently converts into Amadori or Heyns compounds in the presence of aldoses or ketoses, respectively. In the second stage, Amadori and Heyns compounds undergo enolization, releasing amino groups and generating dicarbonyl compounds (Yu et al., 2021), which further react with amino groups to form Maillard reaction products (MRPs), such as melanoidins (Lee, Choi et al., 2024). The final stage involves Strecker degradation, producing heterocyclic compounds such as

pyrazines and furans, which are associated with high consumer acceptance (Lee, Lee et al., 2023). These compounds have also been identified in roasted vegetable oils, including sesame and rapeseed (Yin et al., 2021; Zhang et al., 2022). Despite the advantages of roasting, comprehensive research on the physicochemical properties and sensory profiles of edible insect oils remains limited.

Volatile compounds play a critical role in food quality and consumer acceptance (Li, Li et al., 2025). Headspace solid-phase microextraction (HS-SPME), coupled with gas chromatography-mass spectrometry (GC/MS), is widely used to analyze these compounds, due to its solvent-free operation, rapid extraction, minimal sample requirement, and high sensitivity (Jung et al., 2021). The recently developed SPME-Arrow technique offers enhanced sorbent capacity and sensitivity, making it highly suitable for analyzing volatile compounds in foods (Lee et al., 2019).

In this study, HS-SPME-Arrow-GC/MS was applied to analyze and compare the volatile profiles of oils extracted from five edible insect species, *Tenebrio molitor* (*T. molitor*), *Gryllus bimaculatus* (*G. bimaculatus*), *Locusta migratoria* (*L. migratoria*), *Zophobas atratus* (*Z. atratus*), and *Protaetia brevitarsis* (*P. brevitarsis*), before and after roasting. Among the ten edible insect species approved as food ingredients by the Ministry of Food and Drug Safety in South Korea, these five species were selected for this study. While *T. molitor* has been extensively studied (Lee et al., 2022; Lee et al., 2024; Otero et al., 2020), research on *G. bimaculatus*, *L. migratoria*, *Z. atratus*, and *P.*

brevitarsis remains limited, underscoring the need for further investigation. Roasting conditions were optimized using response surface methodology. The study also evaluated changes in oil quality characteristics, including pH, browning index, color, acid value (AV), peroxide value (PV), iodine value (IV), and fatty acid composition. This work provides the first detailed characterization of roasted edible insect oils, aiming to identify optimal roasting conditions for improving oil quality and consumer acceptability.

Ⅱ. MATERIALS AND METODES

2.1. Insect samples

Five species of frozen, edible insects were used in this study: *T. molitor* (larvae), *G. bimaculatus* (adults), *L. migratoria* (adults), *Z. atratus* (larvae), and *P. brevitarsis* (larvae). All insects were sourced from an insect farm (Jeonge-up, Korea). The insects were reared under controlled conditions (25 - 30 ℃; 60 - 65 % relative humidity) and fed with wheat bran. After that, edible insects were fasted for two days and emptied entrails. The insects were then freeze-dried (FD8508, Ilshin BioBase Co. Ltd., Gyeonggi-do, Korea), homogenized using a blender (BL811DKR, Tefal, Haute-Savoie, France), and stored in freezer (TSE 600D, Thermo Fisher Scientific, USA) at −80 ℃ until further analysis.

2.2 Chemicals and reagents

The reagents used for oil extraction and quality analysis (99.9% ethanol and 0.01 N sodium thiosulfate solution) were purchased from Samchun Chemicals (Seoul, South Korea). Saturated potassium iodide solution was purchased from Junsei Chemical (Tokyo, Japan). Additional reagents for quality and fatty acid analysis were acquired from Daejung (Seoul, Korea). For fatty acid analysis, the internal standard, undecanoic methyl ester, and 14% trifluorobortane-methanol solution were obtained from Sigma-Aldrich (St. Louis, MO, USA). Forty-eight standard volatile compounds, internal standards (ISTD) for volatile analysis, including 2,2-dimethylpropanoic acid, 1-hexyl alcohol-d13, octanal, toluene-d8, 3-octanone, phenyl acetate, 3,4-dimethylphenol, and 2 - methylpyrazine,

and a mixture of C7-C40 alkane standard were also obtained from Sigma-Aldrich. Methanol, used as the diluting solvent for stock solutions, was acquired by Fisher Scientific (Waltham, Massachusetts, USA).

2.3. Optimization of roasting process

Roasting process was optimized using a Box-Behnken design (BBD) based on a previous study (Mansouri et al., 2023). The independent variables include roasting temperature (120 - 180 ℃), time (15 - 30 min), and speed (0.02 - 0.49 ×g). Optimization targeted both unfavorable and favorable volatile compounds in roasted *T. molitor* oils. To optimize roasting conditions for the edible insect, acetic acid, hexanal, nonanal, indole, and phenol were targeted. These volatiles have been reported as undesirable markers in foods such as Chinese liquor, soybeans, and fruit (Gong et al., 2024; Leonard et al., 2023). Favorable volatile compounds of 1-octanol, 2-pentylfuran, d-limonene, 2,5-dimethylpyrazine, and trimethylpyrazine were selected. These compounds are regarded as desirable desirable volatiles to foods such as rapeseed oil, peanut oil, and rice (Gao et al., 2024; Ma et al., 2024; Zhou et al., 2023). The BBD comprised 17 experimental runs, as detailed in Table S1. The experimental design was optimized using response surface methodology (RSM) with Design-Expert software version 7 (Stat-Ease Inc., Minneapolis, MN, USA). All experiments were performed in triplicate (n =3), and data are expressed as mean ± standard deviation (SD).

Table S1. Experimental design and results of the response surface methodology (RSM)

Run	(X_1) Roasting temperature (℃)	(X_2) Roasting time (min)	(X_3) Roasting speed (xg)	(Y_1) Unfavorable volatile compounds[1] (ng/g)	(Y_2) Favorable volatile compounds[2] (ng/g)
1	150	45	0.02	80.74	5.45
2	150	45	0.49	112.70	5.25
3	150	30	0.26	16.72	7.33
4	120	15	0.49	297.95	2.20
5	180	30	0.26	577.12	7.64
6	150	30	0.26	12.07	15.78
7	150	15	0.49	74.8	4.95
8	150	30	0.26	14.94	15.11
9	150	30	0.26	19.00	15.20
10	120	30	0.02	250.78	0.81
11	180	45	0.26	620.83	3.89
12	120	45	0.26	219.21	3.68
13	180	15	0.26	444.73	7.13
14	150	15	0.02	217.53	1.80
15	120	30	0.49	283.61	2.34
16	150	30	0.26	13.61	15.98
17	180	30	0.02	660.49	6.74

[1]acetic acid, hexanal, nonanal, indole, and phenol

[2]1-octanol, 2-pentylfuran, d-limonene, 2,5-dimethylpyrazine, and trimethylpyrazine

2.4. Roasting process of edible insects

Freeze-dried edible insects were roasted using an electric automatic stir-fryer (THDRE-01, Taehwan Automation Ind., Bucheon, Korea). Roasting conditions (temperature, time, and speed) were varied according to the BBD model. In each experiment, 25 g of insects were placed into the stir-fryer. After roasting, the insects were pulverized using a blender and sieved twice through a 14-mesh sieve to ensure particle size uniformity.

2.5. Ultrasound-assisted extraction of insect oils

Oils were extracted using ultrasound-assisted extraction (UAE) method. The UAE method offers reduced processing time and energy consumption, extraction at lower temperatures, and preservation of extract quality (Otero et al., 2020). Five grams of freeze-dried insect samples were mixed with 75 mL ethanol and extracted using ultrasound treatment (Q125 Sonicator with probe part #4435, Qsonica, Newtown, CT, USA). The sonication conditions were set to u amplitude of 70% for 30 min, employing a pulsation mode (30 s on, 30 s off) to avoid overheating. The extracts were centrifudged at 3220 ×g for 10 min, and the supernatant was concentrated using a rotary vacuum evaporator at 35 ℃ (Laborata 4000; Heidolph Instruments, Schwabach, Germany) (Nam et al., 2025).

Unroasted oils were designated as UT for *T. molitor* oil, UG for *G. bimaculatus* oil, UL for *L. migratoria* oil, UZ for *Z. atratus* oil, and UP for *P. brevitarsis* oil. Roasted oils were designated as RT for *T. molitor*

oil, RG for *G. bimaculatus* oil, RL for *L. migratoria* oil, RZ for *Z. atratus* oil, and RP for *P. brevitarsis* oil.

2.6. Physicochemical characteristics

2.6.1. Extraction yields

The extraction yield was calculated by the weight difference between the edible insect weight before and after extraction. The equation is as follows:

$$\text{Extraction yield (\%)} = (w_1 - w_0)/S \times 100 \quad (1)$$

where w_1 is the weight of the flask containing the extracted oil (g); w_0 is the weight of the flask (g); and S is the weight of the dried edible insect powder (g).

2.6.2. pH

The pH of edible insect oils was measured using a pH meter (A211; Thermo Scientific, Waltham, MA, USA).

2.6.3. Color

The color of edible insect oils was examined using a colorimeter (CR-400; Minolta Co., Ltd., Osaka, Japan). The instrument was calibrated using a white plate (L* (lightness) = 92.93, a* (redness) = -0.02, b* (yellowness) = 4.12).

2.6.4. Non-enzymatic browning index

The browning index (BI) was determined using a previously described method (Suri et al., 2020). Samples were prepared by mixing 1 g of the sample with 20 mL of chloroform (1:20, w/v) in a sealed tube. The mixture was then vortexed to ensure homogeneity. Subsequently, the BI was assessed by measuring the absorbance at 420 nm using a microplate reader (SpectraMax M5, Molecular Devices, CA, USA).

2.6.5. Acid, peroxide, and iodine values

The acid value (AV), peroxide value (PV), and iodine value (IV) of the extracted oils were measured using the AOAC method (AOAC, 2005). For AV analysis, 1 g of the sample was used, and titration was performed using a 0.1 N potassium hydroxide ethanolic standard solution. PV was determined using 1 g of the sample, followed by titration with a 0.01 N sodium thiosulfate standard solution. The IV was determined using the Wijs method. For double bond analysis, iodine chloride was added to 0.3 g of oil and subsequently measured by titration with a 0.1 N sodium thiosulfate standard solution.

2.7. Fatty acid composition

The fatty acids were obtained by modifying the Korean Food Codex (MFDS, 2021). 25 mg of insect oils were dissolved in 1 mL of undecanoic acid methyl ester (internal standard) and 2 mL of 0.5 N methanolic sodium hydroxide solution in a 22 mL clear vial, and the mixture was then incubated. It was heated at 100 ℃ for 10 min and cooled on ice. Subsequently, the mixture was combined with 2 mL of 14% trifluoroborane-methanol, followed by heating at 100 ℃ for 10 min

and cooling. Additionally, 1 mL of isooctane and 2 mL of saturated sodium chloride were added to the container, which was then sealed and shaken vigorously for 30 s. Finally, 1 mL of the isooctane layer separated from the aqueous phase was used as an analytical solution.

The fatty acid composition of insect oils was analyzed using gas chromatography combined with a flame ionization detector (Agilent Technologies, Santa Clara, CA, USA). A 2 μL volume of oil was injected in split mode (100:1) at an injector temperature of 225 ℃. The column temperature was initially set at 100 ℃; subsequently increased to 175 ℃ at a rate of 10 ℃/min, held for 10 min; then increased to 210 ℃ at a rate of 5 ℃/min, where it was held for 10 min; and finally increased to 230 ℃ at a rate of 5 ℃/min, and held for 25 min. The detector temperature was 250 ℃. Nitrogen was used as the carrier gas at a flow rate of 1 mL/min through an CP-Sill 88 for FAME column (100 m × 0.25 mm id × 0.2 μm). The gas flow rates were set at 40 mL/min for the makeup gas (nitrogen), 40 mL/min for hydrogen, and 400 mL/min for air. Individual fatty acids were quantified by comparing the retention times and peak areas of the unknown samples with those of 37 standards. These standards included saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA) (Supelco 37 Component FAME Mix #47885-U; SulpecoTM, Philadelphia, PA, USA). Undecanoic acid (C11:0) was used as the internal standard at a concentration of 100 μg/mL. The quantified values were subsequently expressed as percentages (%) of the total fatty acid composition (Lee et al., 2022; Tome-Rodriguez et al., 2023). Furthermore,

the nutritional quality index was evaluated in relation to fatty acid composition using the following equations:

Arteriosclerosis index (AI) =

$$(C_{12:0} + 4 \times C_{14:0} + C_{16:0}) / (\sum MUFA + \sum PUFA) \quad (2)$$

Thrombosis index (TI) =

$$(C_{14:0} + C_{16:0} + C_{18:0}) / [(0.5 \times \sum \text{MUFA}) + (0.5 \times \sum \text{n-6}PUFA) + (3 \times \sum \text{n-3}PUFA) + (\sum \text{n-3}PUFA / \sum \text{n-6}PUFA)] \quad (3)$$

where MUFA is the sum of monounsaturated fatty acid; and PUFA is the polyunsaturated fatty acids in oils.

2.8. Method validation

The HS-SPME-Arrow-GC/MS method was validated by evaluating its linearity, sensitivity, and recovery. The linearity was determined by diluting the stock solutions to six different concentrations. Stock solutions of volatile standards were prepared by diluting precisely weighed amounts of the standard compounds in methanol. 10 µL of the ISTD mixture were added to 0.5 g of odorless coconut oils (Evercoco, Hwaseong, South Korea), which was used as a matrix. Each sample was sealed in a 20 mL headspace vial. The final concentrations of the ISTD added to each sample were as follows: 2 µg/mL each of 2,2-dimethylpropanoic acid, octanal, 1-hexyl alcohol-d13, and 2-methylpyrazine and 0.1 µg/mL each of phenyl acetate, toluene-d8, 3-octanone, and 3,4-dimethylphenol. The following internal standards

were used for each volatile compound group: 2,2-dimethylpropanoic acid for acids; 1-hexyl alcohol-d13 for alcohols and a furan; octanal for aldehydes; 2-methylpyrazine for pyrazines; phenyl acetate for esters, lactones, and a indole; toluene d8 for hydrocarbons and sulfur compounds; 3-octanone for ketones; and 3,4-dimethyl phenol for phenols.

For sensitivity, the limit of detection (LOD) and limit of quantification (LOQ) were measured. LOD is the lowest concentration at which a substance can be detected with confidence, whereas the LOQ represents the lowest concentration that can be accurately quantified. The LOD and LOQ were evaluated based on the standard deviation of the y-intercepts (σ) and the slope (S) of the calibration curve, using the following equations: LOD = 3.3σ/S and LOQ = 10σ/S (Lee, Yoo et al., 2022).

Recovery was conducted using RZ, which possessed the most diverse volatile compounds among all samples. Recovery was measured by spiking the standards into 0.5 g of odorless coconut oil at three levels: the concentrations of the middle level were based on the contents of the edible insect oil, whereas the high level spiked the 2 times of the middle level, and the low level spiked 1/2 of the middle level (Kim et al., 2022). This experiment was performed in triplicate.

2.9. Analysis of volatile compounds

0.5 g of edible insect oil and 10 μL of internal standard mixture were sealed into a 20 mL headspace vial and stirred in an agitator at 40 ℃ for 10 min at 500 rpm. For extraction of volatile compounds, 120 μm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS)

SPME-Arrow fiber (PAL System, Zwingen, Switzerland) was utilized with an autosampler (PAL RSI 85, PAL System). It was subsequently injected into the GC injector port set to splitless mode and desorbed for 5 min at 220 ℃.

The gas chromatography-mass spectrometry (GC-MS) analysis was performed using an Agilent 8890 gas chromatograph connected to an Agilent 7000E triple quadrupole mass spectrometer (Agilent Technologies, Santa Clara, CA, USA). The samples were separated using an HP-5MS column (60 m × 0.25 mm inner diameter × 0.25 μm film thickness; Agilent J&W Scientific, Inc., Santa Clara, CA, USA). The GC program was configured as follows: initial temperature 45 ℃ for 10 min, increased to 100 ○C at a rate of 2 ℃/min; then increased to 230 ℃ at a rate of 3 ℃/min and maintained for 3 min. Helium was used as a carrier gas at a constant flow rate of 1.0 mL/min. The ion source and MS transfer line were maintained at temperatures of 230 ℃ and 280 ℃, respectively. The samples were injected in full scan mode (mass range of 30 - 550 m/z) and selected ion monitoring (SIM) mode using electron ionization at 70 eV.

Volatile compounds were identified by comparing their mass spectra with the NIST 20 library (National Institute of Standards and Technology, Gaithersburg, MD, USA). The experimental KI values were compared with literature KI values using a mixture of C7 - C40 hydrocarbons. Each volatile compound was quantified using a calibration curve. A standard solution for the calibration curve was prepared using volatile compound standards from the same group. ISTD was added at

the same concentration as that used for the samples. Calibration curves for each compound were established using the ratio of the peak areas (analyte/ISTD). The peak area of each volatile compound was measured using the quantifier ions. The KI values, quantifier, and qualifier ions for each compound are listed in Table S2.

Table S2. Kovats retention indexes, quantifier and qualifier ions, and aroma descriptions of the 48 volatile compounds identified in the ten edible insect oil samples

Volatile compounds	KI^{L}	KI^{E}	Qualifier ions (m/z)	Quantifier ions (m/z)	Aroma description[i]
Acids					
2-methylbutanoic acid	870	870	41, 57	74	butter, cheese, fermented
2-methylpropanoic acid	775	770	43, 73	88	burnt, butter, cheese
3-methylbutanoic acid	861	866	43, 60	87	acid, cheese, fat
acetic acid	638	628	43, 45	60	acid, fruit, pungent, sour
butanoic acid	804	805	55, 60	73	butter, cheese, must
decanoic acid	1380	1383	60, 73	129	apricot, cocoa, coconut
dodecanoic acid	1580	1579	73, 129	157	fat, fruit, metal
hexanoic acid	997	999	60, 73	87	acid, cheese, fermented
nonanoic acid	1283	1285	41, 60	73	fat, green, sour
octanoic acid	1203	1206	60, 101	115	acid, cheese, fat
pentanoic acid	898	894	55, 60	73	acid, cheese, fecal
propanoic acid	702	706	45, 57	57	fat, pungent, rancid
Alcohols					
1-decanol	1285	1291	55, 83	112	fat, oil, orange
1-octanol	1089	1090	41, 56	70	citrus, detergent, fat, fruit
1-pentanol	781	784	42, 55	70	almond, balsamic, fruit
2,3-butanediol	782	784	45, 57	75	cream, floral, fruit, herb
2-phenylethanol	1132	1131	91, 92	122	corn flakes, floral, fruit
Aldehydes					
2-methylbutanal	689	692	41, 57	86	almond, chocolate, cocoa
3-methylbutanal	689	685	44, 58	71	almond, balsamic, fruit
benzaldehyde	979	976	51, 77	106	almond, berry, bitter
heptanal	913	917	41, 55	70	bread, burnt, caramel
hexanal	817	821	44, 56	72	fat, fish, fresh
nonanal	1121	1122	57, 70	98	citrus, cucumber, fat
phenylacetaldehyde	1063	1061	91, 65	120	berry, floral, flower,
Esters					
ethyl lactate	836	833	43, 45	75	butter, cream, floral, fruit
ethyl octanoate	1199	1201	88, 101	127	apricot, banana, brandy
methyl decanoate	1333	1344	74, 87	99	fresh, soap, wine
methyl octanoate	1138	1144	74, 127	158	fruit, orange, sweet
methyl salicylate	1217	1213	92, 120	152	almond, caramel, fresh
Furan					
2-pentylfuran	1002	1006	81,95	138	butter, floral, fruit
Hydrocarbons					
d-limonene	1055	1046	68, 93	136	citrus, mint
p-xylene	888	885	77, 91	106	cold meat fat, metal
o-xylene	908	907	77, 91	106	geranium
Indole					

indole	1316	1314	63, 90	117	animal, burnt, fecal
Ketones					
2-decanone	1201	1209	43, 58	71	fat, fruit
2-heptanone	901	906	58, 71	114	bell pepper, blue cheese
2-nonanone	1104	1107	43, 58	71	fragant, fruit, green
acetophenone	1079	1081	77, 105	120	almond, animal, flower
Lactones					
γ-butyrolactone	924	929	42, 56	86	caramel, cheese, fruit
γ-nonalactone	1387	1386	55, 85	99	apricot, cocoa, coconut
Phenols					
2-methoxyphenol	1106	1104	81, 109	124	bacon, burnt, clove
4-methylphenol	1086	1089	77, 90	107	animal, horse, leather
phenol	997	998	51, 77	107	medicine, phenol, sharp
Pyrazines					
2,3-dimethylpyrazine	932	934	40, 67	108	caramel, cocoa, dry
2,5-dimethylpyrazine	928	925	42, 81	108	burnt, cocoa, coffee
trimethylpyrazine	1020	1017	42, 81	122	burnt, cotton candy, licorice
Sulfur compounds					
dimethyl sulfone	931	937	45, 79	94	burnt, sulfur
methional	924	921	61, 74	104	baked potatoes, caramel, potato

[L]Kovats index reported by NIST is available at https://webbook.nist.gov/chemistry/cas-ser for HP-5MS columns or equivalents, [E]Kovats index was calculated using nalkanes for the HP-5MS column. [i]Aroma description from https://www.vcf-online.nl/VcfCompoundSearch.cfm.

2.10. Sensory evaluation

The samples (1 g each) were sealed in brown screw-cap vials (20 mL; Samwoo Kurex, Seoul, Korea), and labeled with a 3-digit random code. To avoid olfactory fatigue and adaptation, evaluations were conducted over two days with five samples assessed per day, allowing sufficient rest intervals between the samples. Additionally, to minimize errors due to presentation order, a Williams Latin square design was employed (Williams, 1949), and a sequential monadic order was used, where each sample was evaluated completely before proceeding to the next.

A total of 74 consumers participated in this study, including 16 males (21.6 %) and 58 females (78.4 %), with an average age of 27.8 ± 10.2 years. Consumers rated the odor liking of each sample on a 9-point hedonic scale (1 = extremely dislike, 5 = neither like nor dislike, 9 = extremely like) and the odor intensity on a 9-point intensity scale (1 = not detectable, 9 = extremely strong). In addition, they were asked to freely describe the odor characteristics of each sample. To minimize the influence of visual attributes (e.g., color, clarity, and viscosity), evaluations were conducted under red lighting in individual sensory booths.

All procedures were performed in compliance with the relevant laws and institutional guidelines and approved by The Catholic University of Korea Institutional Review Board (approval number: 1040395-202407-22). In addition, the privacy rights of the human subjects were observed, and informed consent was obtained.

2.11. Statistical analysis

2.11.1. Quality characteristics and volatile analysis

Statistical analyses of the data were performed via a one-way analysis of variance (ANOVA) using SPSS version 26.0 (Statistical Package for the Social Sciences, IBM-SPSS Inc., Chicago, IL, USA). Multiple comparisons between samples were performed using Duncan's multiple range test ($p < 0.05$). A heat map was generated using MetaboAnalyst (version 5.0). All experiments were performed in triplicate. Data are expressed as mean ± SD (n = 3).

2.11.2. Sensory evaluation

For odor liking and intensity data, ANOVA was conducted using a generalized linear model (GLM) to analyze the effects of species and roasting, which were considered fixed factors. The effect of consumers was considered as random factor. The following GLM was used: liking or intensity = species + roasting + species × roasting + consumer. When significant differences were observed ($p < 0.05$), Duncan's multiple range test was used for post hoc analysis. Additionally, paired t-tests were performed to further analyze the differences in odor liking and intensity based on the roasting status (before vs. after roasting) within each species ($p < 0.05$).

Textural data from the open-ended questions were analyzed following the procedure suggested by Symoneaux et al. (2012). Odor descriptors with similar meanings were grouped into representative descriptors (e.g.,

peanut-like, almond-like, and walnut-like were categorized as nutty). Textural analysis was conducted to compute the frequency of the odor descriptors mentioned for each sample. Only descriptors cited with a frequency of 10 % or higher, or those with significantly higher observed frequencies than expected values based on chi-square per cell analysis ($p < 0.05$), were included in the results. To visually summarize the relationship between samples and odor descriptors, correspondence analysis (CA) was performed and based on the CA results, hierarchical clustering on principal component analysis (HCPC) was conducted using FactoMineR package (Lê et al., 2008) in R language.

Ⅲ. RESULTS AND DISCUSSION

3.1. Roasting process optimization using RSM

3.1.1 Optimization based on unfavorable volatile compounds

Roasting conditions were optimized using RSM based on the Box-Behnken design (BBD). The optimization aimed to minimize the levels of five volatile compounds, namely acetic acid, hexanal, nonanal, phenol, and indole, which were identified as undesirable volatiles in insect oils. The independent variables were roasting temperature (X_1), time (X_2), and speed (X_3). The developed model was statistically significant ($p < 0.0001$), as indicated by an F-value of 46.93. In addition, the high coefficient of determination (R^2 = 0.9837) demonstrated excellent model fit and predictive capability. The relationship between the three roasting parameters and the concentration of undesirable volatile compounds in edible insect oil is explained as follows:

$$Y = 1.201 - 2095.53X_1 + 3563.16X_2 + 1.806X_3 + 63.71X_1X_2 - 1688.95X_1X_3 + 2672.46X_2X_3 + 350.98X_1^2 + 29.34X_2^2 + 6.79X_3^2 \quad (4)$$

Three-dimensional (3D) response surface plots depicting the interactions between the content of volatile compounds in sample and experimental levels of each variable are shown in Fig. 1. The level of unfavorable compounds in edible insect oils was the lowest at a roasting temperature of 150-160 ℃ and a time of 30-37.5 min (Fig. 1a). At a constant roasting speed of 0.26 ×g, the volatile compounds associated

with negative sensory perceptions were minimized within the same temperature range (150–160 ℃) (Fig. 1b). Additionally, a roasting speed of 0.26 ×g and a time of 30 - 37.5 min resulted in the lowest levels of five volatile markers (Fig. 1c). Based on these results, the optimal roasting conditions for minimizing unfavorable volatile compounds were determined as 150 ℃ for 30 min at a speed of 0.26 ×g.

3.1.2 Optimization based on favorable volatile compounds

To maximize sensory appeal, the roasting was also optimized using five favorable volatile compounds (1-octanol, 2-pentylfuran, d-limonene, 2,5-dimethylpyrazine, and trimethylpyrazine) as response variables. This model developed for favorable volatiles was also statistically significant ($F = 54.23$, $p < 0.0001$), with an excellent fit to the data ($R^2 = 0.9859$). The relationship between the three roasting parameters and the concentration of favorable volatile compounds in edible insect oil is explained as follows:

$$Y = -89{,}393.73 - 3.57X_1 - 57.65X_2 - 1.344X_3 - 1.18X_1X_2 - 4.59X_1X_3 - 43.45X_2X_3 - 5.15X_1^2 - 5.18X_2^2 - 50{,}504.59X_3^2 \quad (5)$$

Under the same optimized conditions determined for minimizing unfavorable volatile compounds, the concentrations of favorable volatile compounds were simultaneously maximized (Fig. 1d–f). These plots demonstrate that roasting at 150 ℃ for 30 min at a speed of 0.26 ×g also enhanced the generation of favorable volatile compounds.

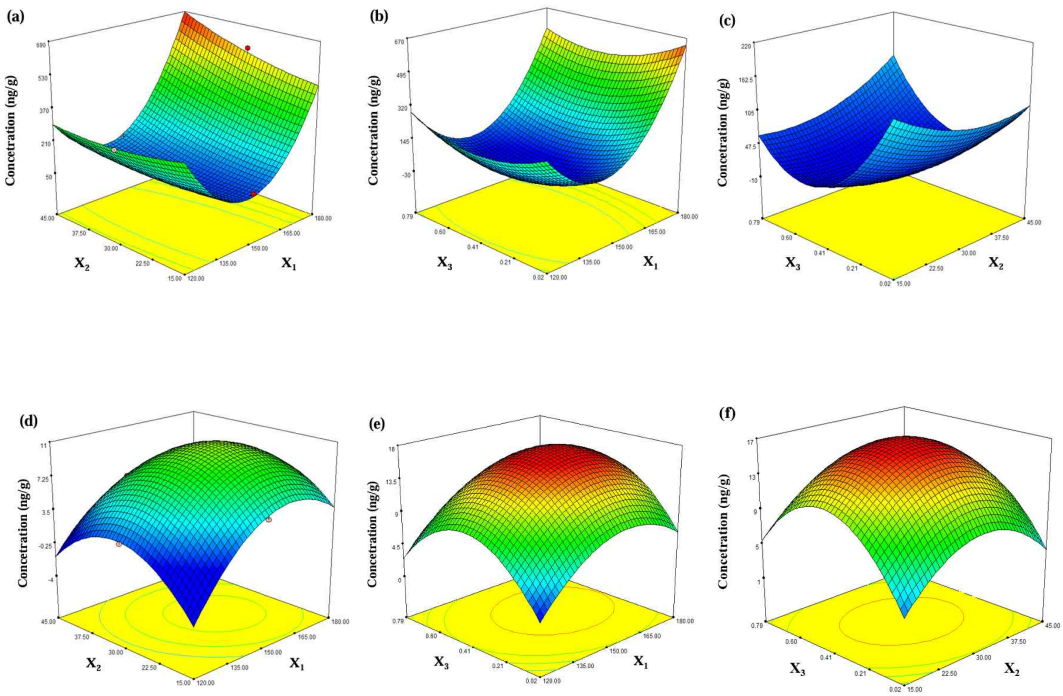

Figure 1. Optimization of the roasting conditions for edible insects utilizing response surface methodology (RSM). (a)-(c) was optimization models for reducing unfavorable volatile compounds; (d)-(f) was optimization models for increasing favorable volatile compounds. Interactions between (a) and (d) X_1 (Roasting temperature) and X_2 (Roasting time), (b) and (e) X_1 (Roasting temperature) and X_3 (Roasting speed), and (c) and (f) X_2 (Roasting time) and X_3 (Roasting speed)

3.2. Physicochemical characteristics

Table 1 shows the results of the extraction yield, pH, color, BI, AV, PV, and IV for the oils extracted from roasted and unroasted edible insects. The extraction yields of insect oils were higher in the five roasted samples compared to the unroasted samples. Among the samples, RZ exhibited the highest extraction yield at 42.73 % ($p < 0.05$). The greatest increase of 3.64 % was observed between unroasted and roasted oil extraction from *Z. atratus* (UZ: 39.09 %; RZ: 42.73 %). Additionally, the extraction yields of UT and RT were 30.21 % and 32.48 %, respectively. A previous study using n-hexane reported a comparable extraction yield of 29.24 % for *T. molitor* oil (Lee et al., 2022). The increase in the oil extraction yield can be attributed to roasting-induced structural modifications in the insect tissue, including disruption of cell walls and increased porosity, which facilitate oil release (Suri et al., 2020). Therefore, roasting increased extraction efficiency of edible insect oils.

The pH of UL was the lowest among all the samples. However, no significant differences were observed between roasted and unroasted samples. This finding is consistent with previous reports on the differences between green and roasted coffee beans (Franca et al., 2005).

Color analysis revealed that L^* values decreased in all roasted oil samples, whereas the a* and b^* values increased compared to unroasted samples. A lower value of L^* values indicates that the brightness of samples decreases, and the trend in the a^* and b^* value rising after

roasting indicates a shift in the color spectrum from green to red and blue to yellow (Cheragheshahi et al., 2025). Notably, the a^* values were the highest in RL, showing significant differences compared with the other oils ($p < 0.05$). A comparable change in a* values was reported for roasted rapeseed oil by Zhang et al. (2022). These changes in oil color result from the Maillard reaction and the formation of browning-related byproducts in edible insects during roasting (Cheragheshahi et al., 2025).

BI is suitable for evaluating the progress of the Maillard reaction (Zhang et al., 2022). The BI values were significantly higher in roasted samples than in unroasted ones ($p < 0.05$), with increases ranging from 0.04 to 0.24. The color change from light yellow to dark brown was attributed to the formation of MRPs (Hu et al., 2024). These observations were consistent with previous research using flaxseed oil roasted in a microwave oven (Suri et al., 2020).

AV, PV, and IV were analyzed to evaluate the impact of roasting on the nutritional quality of edible insects (Table 1). AVs were significantly higher in all roasted samples (58.21-111.38 mg/g) than unroasted oils (55.23-100.13 mg/g) ($p < 0.05$). The high AV was mainly attributed to an increase in the free fatty acid content owing to thermal oxidation and hydrolysis (Zheng et al., 2024). Furthermore, PV represents the primary oxidation product and indicates the oxidative stability of the oil (Hu et al., 2024). PVs were also significantly higher in the roasted samples than in unroasted samples ($p < 0.05$). However, PVs of all oils remained below the standard Codex Alimentarius limit of 15 meq/kg for vegetable

oils (Alimentarius, 2023), suggesting accptable oxidative stability. These findings are consistent with previous studies on flaxseed and sesame oils, which reported increased AV and PV following thermal treatment (Hu et al., 2024; Sun et al., 2022; Suri et al., 2020).

IV is an index of unsaturation of fatty acid, which is an important quality characteristic of oil. IVs were significantly higher in roasted samples than the unroasted samples ($p < 0.05$), reflecting greater oxidative instability (Hromis et al., 2022). *T. molitor* oil exhibited the highest IVs (UT: 96.69 g/100 g; RT: 98.97 g/100 g), comparable to canola oil (99.77 g/100 g) and Safflower oil (92-105 g/100 g) (De Jesus-Hernandez et al., 2023). *G. bimaculatus*, *L. migratoria*, and *Z. atratus* oils exhibited IVs similar to those of sunflower oil (78-90 g/100 g) according to Codex standards (Alimentarius, 2023). It was therefore confirmed that oils extracted from edible insects possess quality characteristics comparable to those of conventional vegetable oils.

Table 1. Comparison of extraction yield, color parameters, browning index, and chemical quality indicators of oils extracted from roasted and unroasted edible insects

	UT	RT	UG	RG	UL	RL	UZ	RZ	UP	RP
Extraction yield (%)	30.21±0.78^{d}	32.48±0.15^{c}	18.34±0.26^{f}	20.49±0.30^{e}	7.46±0.32^{j}	8.69±0.29^{j}	39.09±0.57^{b}	42.73±0.33^{a}	10.80±0.07^{h}	12.90±0.44^{g}
pH	7.66±0.41^{a}	7.68±0.01^{a}	6.54±0.03^{c,d}	6.58±0.03^{c}	6.29±0.07^{d}	6.68±0.06^{c}	7.17±0.21^{b}	7.31±0.09^{b}	6.46±0.01^{c,d}	6.47±0.05^{c,d}
L*	31.60±0.85^{c}	28.69±0.08^{e}	26.94±0.08^{g}	25.91±0.13^{h}	24.40±0.10^{i}	22.55±0.13^{j}	36.58±0.22^{a}	32.49±0.12^{b}	30.41±0.10^{d}	27.99±0.02^{f}
a*	−0.56±0.12^{f}	0.79±0.06^{f}	0.58±0.04^{d}	2.00±0.10^{c}	3.59±0.19^{b}	6.32±0.10^{a}	−0.59±0.11^{f}	2.06±0.33^{c}	−0.59±0.10^{f}	−0.05±0.13^{e}
b*	2.45±0.49^{f}	2.57±0.28^{f}	7.25±0.21^{e}	9.00±0.18^{c}	2.33±0.26^{f}	10.54±0.55^{b}	0.25±0.01^{h}	15.92±0.35^{a}	1.10±0.06^{g}	8.38±0.16^{d}
BI	0.09±0.01^{f}	0.33±0.05^{a,b}	0.27±0.02^{c}	0.32±0.01^{a,b}	0.29±0.01^{b,c}	0.33±0.02^{a,b}	0.15±0.02^{e}	0.22±0.02^{d}	0.15±0.03^{e}	0.35±0.02^{a}
AV (mg/g)	100.13±0.19^{b}	111.38±0.17^{a}	86.33±0.02^{d}	91.85±0.07^{c}	74.88±0.11^{g}	80.34±0.25^{e}	55.23±0.10^{j}	58.21±0.14^{i}	71.92±0.05^{h}	77.50±0.05^{f}
PV (meq/kg)	0.73±0.06^{i}	1.33±0.11^{h}	10.22±0.59^{b}	12.90±0.02^{a}	7.30±0.18^{d}	8.89±0.01^{c}	3.49±0.17^{g}	5.97±0.11^{e}	4.73±0.29^{f}	6.24±0.29^{e}
IV (g/100 g)	96.69±0.15^{b}	98.97±0.38^{a}	82.49±0.50^{f}	84.53±0.07^{e}	88.79±0.09^{d}	89.71±0.80^{c}	80.35±0.25^{h}	81.38±0.58^{g}	69.72±0.40^{j}	71.82±0.26^{i}

UT, Unroasted *Tenebrio molitor* oil; RT, Roasted *Tenebrio molitor* oil; UG, Unroasted *Gryllus bimaculatus* oil; RG, Roasted *Gryllus bimaculatus* oil; UL, Unroasted *Locusta migratoria* oil; RL, Roasted *Locusta migratoria* oil; UZ, Unroasted *Zophobas atratus*; RZ, Roasted *Zophobas atratus* oil; UP, Unroasted *Protaetia brevitarsis* oil; RP, Roasted *Protaetia brevitarsis* oil; BI, Browning index; AV, Acid value; PV, Peroxide value; IV, Iodine value. All results are expressed as the mean ± standard deviation of three replicates (n = 3); $^{a-j}$values in rows with different letters are significantly different at $p < 0.05$, according to Duncan's multiple range test.

3.3. Fatty acid composition

The fatty acid compositions of unroasted and roasted insect oils are presented in Table 2. Although the total fatty acid content varied with roasting, the composition remained stable. Sun et al (2022). reported that alterations in fatty acid composition occur at roasting temperatures above 200 ℃

Oleic acid (C18:1), linoleic acid (C18:2), and palmitic acid (C16:0) were the predominant fatty acids in *T. molitor, G. bimaculatus, and Z. atratus* oils, aligning with previous reports (Lee et al., 2022; Otero et al., 2020). The oleic acid (C18:1) content was 41.96 % for UT and 42.37 % for RT, which is similar to that found in sesame oil (40.3-41.35 %) (Kheirati Rounizi et al., 2021). Moreover, the content of oleic acid was the highest in *P. brevitarsis* reaching 58.32 % (UP) and 58.97 % (RP), comparable to 57.82 % of avocado oil (Krumreich et al., 2024).

As essential fatty acids, linoleic acid (omega-6) and α-linolenic acid (omega-3) function as precursors to other fatty acids. These two fatty acids were observed as the predominant fatty acids in *L. migratoria*, with α-linolenic acid present at higher levels than in the other insect species (UL: 25.31 %; RL: 24.68 %). These findings are consistent with the fatty acid composition of hemp seed oil, with contents ranging from 24.55 % to 25.73 % (Alonso-Esteban et al., 2023). Linoleic acid (C18:2, n-6) is a precursor to ɣ-linolenic acid (C18:3, n-6), which exhibits anti-inflammatory, antimicrobial, and antiplatelet properties (Alonso-Esteban et al., 2023). Similarly, α-linolenic acid serves as a

precursor to eicosapentaenoic acid (EPA, C20:5, n-3) and docosahexaenoic acid (DHA, C22:6, n-3). These fatty acids are important for maintaining normal blood cholesterol levels and preventing cardiovascular disease (Krumreich et al., 2024). These results indicate that edible insect oils represent a valuable dietary source of α-linolenic acid (C18:3, n-3) and linoleic acid (C18:2, n-6), which cannot be synthesized in the human body.

The total contents of saturated fatty acid (SFA), monounsaturated fatty acid (MUFA), and polyunsaturated fatty acid (PUFA) derived from insect oils are shown in Table 2. *Z. atratus* oil exhibited the highest SFA content, whereas the MUFA and PUFA contents were the highest in *P. brevitarsis* and *L. migratoria* oils, respectively. A PUFA/SFA ratio of ≥ 0.45 is associated with cardiovascular and cancer preventive effects (Wood et al., 2004). The PUFA/SFA ratios of oils extracted from *T. molitor*, *G. bimaculatus*, *L. migratoria*, and *Z. atratus* ranged from 0.59 and 1.46. Among the samples, *L. migratoria* and *T. molitor* oils showed PUFA/SFA ratios of ≥ 1.

The atherogenic index (AI) and thrombogenic index (TI) are key indicators used to assess the nutritional quality of foods and their associated health risks such as cardiovascular disease (Otero et al., 2020), with lower values indicate greater health benefits. *L. migratoria* and *P. brevitarsis* oils showed the lowest values, suggesting that they may contribute to the prevention of cardiovascular diseases. Interestingly, *L. migratoria* oil demonstrated the highest PUFA/SFA ratio and the lowest AI and TI values, suggesting valuable lipid-based nutrients. In

summary, edible insect oil can serve as a suitable substitute for vegetable oil in human diets, and as a sustainable source of lipids.

Table 2. Fatty acid compositions (%) of oils extracted from five edible insect speciess (*Tenebrio molitor, Gryllus bimaculatus, Locusta migratoria*, *Zophobas atratus,* and *Protaetia brevitarsis seulensis*)

Fatty acid (%)	UT	RT	UG	RG	UL	RL	UZ	RZ	UP	RP
C6:0	nd	nd	nd	nd	0.01±0.00^{c}	0.01±0.00 ^{c}	0.63±0.01^{a}	0.57±0.00^{b}	nd	nd
C10:0	0.48±0.00^{d}	0.44±0.01^{e}	0.53±0.01^{c}	0.57±0.02^{c}	0.57±0.04^{c}	0.55±0.01^{c}	0.61±0.0^{b}	0.56±0.00^{c}	0.75±0.02^{a}	0.61±0.05^{b}
C12:0	0.34±0.00^{a}	0.29±0.00^{b}	0.23±0.00^{d}	0.25±0.00^{c}	0.22±0.00^{e}	0.21±0.00^{e}	0.09±0.00^{f}	0.08±0.00^{g}	0.02±0.00^{i}	0.03±0.00^{h}
C13:0	0.08±0.00^{a}	0.05±0.00^{b}	nd	nd	0.01±0.00^{e}	0.01±0.00^{e}	0.03±0.00^{d}	0.03±0.00^{c}	nd	nd
C14:0	3.79±0.01^{a}	2.81±0.01^{b}	0.78±0.00^{g}	0.77±0.00^{g}	1.07±0.00^{e}	1.02±0.02^{f}	1.26±0.00^{c}	1.22±0.00^{d}	0.72±0.10^{h}	0.71±0.00^{h}
C14:1	0.02±0.01^{c}	0.02±0.00^{c}	nd	nd	nd	nd	nd	nd	0.11±0.03^{b}	0.14±0.03^{a}
C15:0	0.16±0.00^{b}	0.13±0.00^{c}	0.11±0.00^{e}	0.11±0.00^{d}	0.09±0.00^{f}	0.09±0.00^{f}	0.37±0.00^{a}	0.37±0.00^{a}	nd	nd
C16:0	18.15±0.02^{c}	16.43±0.46^{d}	24.98±0.01^{b}	25.04±0.12^{b}	15.46±0.05^{e}	15.53±0.03^{e}	30.56±0.06^{a}	30.64±0.03^{a}	17.99±0.05^{c}	17.88±0.10^{c}
C16:1	1.61±0.00^{c}	2.22±0.01^{b}	1.62±0.00^{c}	1.60±0.00^{c}	0.90±0.01^{d}	0.90±0.00^{d}	2.23±0.03^{b}	2.16±0.03^{b}	9.59±0.18^{a}	9.70±0.25^{a}
C17:0	0.19±0.00^{f}	0.15±0.00^{g}	0.26±0.00^{d}	0.25±0.01^{e}	0.57±0.00^{c}	0.56±.0.00^{c}	0.63±0.00^{a}	0.61±0.00^{b}	nd	nd
C17:1	0.15±0.00	0.15±0.00	nd	nd	0.12±0.00	0.13±0.00	nd	nd	nd	nd
C18:0	3.06±0.01^{d}	2.76±0.02^{e}	7.03±0.01^{b}	7.03±0.04^{b}	10.48±0.03^{a}	10.50±0.06^{a}	5.77±0.02^{c}	5.78±0.00^{c}	2.73±0.01^{e}	2.71±0.01^{e}
C18:1 (trans)	nd	nd	0.10±0.01^{a}	0.11±0.01^{a}	0.05±0.01^{d}	0.05±0.01^{c}	nd	nd	0.06±0.01^{c}	0.07±0.01^{b}
C18:1	41.96±0.06^{c}	42.37±0.24^{b}	25.93±0.02^{g}	25.78±0.11^{g}	27.61±0.07^{f}	28.23±0.16^{e}	33.25±0.02^{d}	33.32±0.02^{d}	58.32±0.12^{b}	58.97±0.16^{a}
C18:2 (trans)	nd	nd	0.01±0.01^{b}	0.01±0.01^{a}	nd	nd	nd	nd	nd	nd
C18:2	27.89±0.02^{c}	29.87±0.17^{b}	35.82±0.04^{a}	35.90±0.31^{a}	16.27±0.24^{e}	16.38±0.23^{e}	22.92±0.06^{d}	23.02±0.01^{d}	7.53±0.09^{f}	7.14±0.03^{f}

C20:0	0.12±0.00^{e}	0.11±0.00^{e}	0.31±0.01^{c}	0.34±0.01^{b}	0.19±0.01^{d}	0.19±0.02^{d}	0.13±0.01^{e}	0.13±0.01^{e}	0.53±0.01^{a}	0.53±0.01^{a}
C18:3 (γ)	nd	nd	0.06±0.00^{d}	0.07±0.00^{c}	nd	nd	0.02±0.00^{e}	0.02±0.00^{e}	0.09±0.00^{b}	0.09±0.00^{a}
C20:1	0.16±0.00^{c}	0.14±0.00^{d}	0.04±0.00^{g}	0.04±0.00^{g}	nd	nd	0.09±0.00^{e}	0.09±0.00^{f}	0.17±0.00^{b}	0.17±0.00^{a}
C18:3 (α)	1.15±0.00^{d}	1.37±0.01^{c}	1.47±0.01^{b}	1.40±0.00^{b,c}	25.31±0.06^{a}	24.68±0.13^{a}	0.83±0.00^{e}	0.83±0.00^{e}	0.20±0.01^{f}	0.10±0.00^{g}
C20:2	0.06±0.02^{d,e}	0.14±0.01^{b}	0.07±0.01^{c}	0.08±0.01^{c,d}	0.18±0.02^{a}	0.18±0.01^{a}	0.04±0.00^{e}	0.04±0.00^{e}	0.05±0.00^{e}	0.05±0.00^{e}
C22:0	0.00 ± 0.00^{d}	0.01±0.00^{c,d}	nd	nd	0.04±0.00^{b,c,d}	0.09±0.08^{a}	0.02±0.00^{b,c,d}	0.02±0.00^{b,c,d}	0.06±0.00^{a,b}	0.05±0.00^{a,b,c}
C22:1	nd	nd	0.01±0.00^{c}	0.01±0.00^{c}	nd	nd	nd	nd	0.04±0.00^{a}	0.04±0.00^{b}
C20:3	nd	nd	0.02±0.00^{c}	0.02±0.00^{d}	0.05±0.00^{a}	0.05±0.00^{a}	nd	nd	0.03±0.00^{b}	0.03±0.00^{b}
C20:4	nd	nd	0.03±0.00^{b}	0.03±0.00^{b}	0.06±0.00^{a}	0.05±0.00^{a}	nd	nd	nd	nd
C23:0	0.19±0.00^{a}	0.10±0.00^{b}	nd	nd	nd	nd	nd	nd	nd	nd
C22:2	nd	nd	nd	nd	0.01±.0.00	0.01±0.00	nd	nd	nd	nd
C20:5	nd	nd	nd	nd	nd	nd	nd	nd	0.01±0.01^{b}	0.01±0.00^{a}
C24:1	nd	nd	nd	nd	0.15±0.01^{a}	0.13±0.01^{b}	nd	nd	nd	nd
ΣSFA	26.56±0.03^{d}	23.28±0.43^{e}	34.24±0.02^{b}	34.36±0.17^{b}	28.70±0.09^{c}	28.62±0.14^{c}	40.10±0.06^{a}	40.00±0.02^{a}	22.82±0.02^{f}	22.52±0.11^{g}
ΣMUFA	43.89±0.05^{d}	44.90±0.26^{c}	27.70±0.01^{h}	27.53±0.13^{h}	28.83±0.08^{g}	29.50±0.12^{f}	35.58±0.03^{e}	35.57±0.03^{e}	68.29±0.09^{b}	69.10±0.42^{a}
ΣPUFA	29.09±0.04^{e}	31.38±0.18^{d}	37.47±0.03^{c}	37.49±0.31^{c}	41.87±0.17^{a}	41.35±0.15^{b}	23.81±0.07^{f}	23.92±0.01^{f}	7.91±0.09^{g}	7.42±0.03^{h}
PUFA/SFA	1.10±0.00^{c}	1.35±0.03^{b}	1.09±0.00^{c}	1.09±0.01^{c}	1.46±0.01^{a}	1.44±0.01^{a}	0.59±0.00^{d}	0.60±0.00^{d}	0.35±0.00^{e}	0.35±0.00^{e}
AI	0.46±0.00^{b}	0.37±0.01^{e}	0.43±0.00^{d}	0.44±0.00^{c}	0.28±0.00^{f}	0.28±0.00^{f}	0.60±0.00^{a}	0.60±0.00^{a}	0.27±0.00^{g}	0.27±0.00^{g}
TI	0.63±0.00^{c}	0.53±0.01^{e}	0.90±0.00^{b}	0.91±0.01^{b}	0.27±0.00^{f}	0.27±0.00^{f}	1.18±0.00^{a}	1.18±0.00^{a}	0.55±0.00^{d}	0.55±0.00^{d}

UT, Unroasted *Tenebrio molitor* oil; RT, Roasted *Tenebrio molitor* oil; UG, Unroasted *Gryllus bimaculatus* oil; RG,

Roasted *Gryllus bimaculatus* oil; UL, Unroasted *Locusta migratoria* oil; RL, Roasted *Locusta migratoria* oil; UZ, Unroasted *Zophobas atratus*; RZ, Roasted *Zophobas atratus* oil; UP, Unroasted *Protaetia brevitarsis* oil; RP, Roasted *Protaetia brevitarsis* oil; SFA, Saturated fatty acid; MUFA, Monounsaturated fatty acid; PUFA, Polyunsaturated fatty acid; AI, Arteriosclerosis index; TI, Thrombosis index. All results are expressed as the mean ± standard deviation of three replicates (n = 3); $^{a-j}$values in row with different letters are significantly different as $p < 0.05$ according to Duncan's multiple range test; nd: not detected.

3.4. Method validation

Method validation for the quantification of 48 volatile compounds includes evaluation of calibration curves, linearity, LOD, and LOQ, as shown in Table S3. For linearity, the correlation coefficients were between 0.9800 and 0.9997 for all compounds across the entire concentration range studied. LOQ varied between 60.25 ng/g and 197.38 ng/g for acids, 14.74 ng/g-99.06 ng/g for alcohols, 19.22 ng/g-41.63 ng/g for aldehydes, 14.39 ng/g-19.67 ng /g for esters, 17.65 ng/g for 2-pentylfuran, 9.06 ng/g-18.67 ng/g for hydrocarbons, 47.89 ng/g for indole, 3.22 ng/g-4.69 ng/g for ketones, 4.73 ng/g-5.00 ng/g for lactones, 3.27 ng/g-4.97 ng/g for phenols, 9.00 ng/g-9.41 ng/g for pyrazines, and 9.42 ng/g - 19.84 ng/g for sulfur compounds.

Accuracy was analyzed by calculating the percentage recovery after adding standards to odorless coconut oil (Table S4). For all cases, the recoveries ranged from 90.09 to 109.98 % at concentration of spiking 1, from 90.13 to 107.07 % at concentration of spiking 2, and from 90.98 to 108.39 % at concentration of spiking 3. The RSDs of the 48 volatile compounds were below 10 % and complied with the Codex standards (Alimentarius, 2015).

Table S3. Calibration curves, linear ranges, correlation coefficients (R^2), limits of detection (LOD), and quantification (LOQ) for the 48 volatile compounds analyzed using HS-SPME-Arrow-GC/MS

Volartile compounds	Linearity			LOD (ng/g)	LOQ (ng/g)
	Calibration curves	R^2	Range (ng/g)		
Acids					
2-methylbutanoic acid	y = 4.1422x - 0.1616	0.9996	100-8000	21.60	65.44
2-methylpropanoic acid	y = 0.6275x + 0.0020	0.9837	100-6000	17.22	52.19
3-methylbutanoic acid	y = 1.1236x - 0.0834	0.9888	200-20000	64.01	193.96
acetic acid	y = 12.375x + 7.7969	0.9926	200-200000	65.14	197.38
butanoic acid	y = 3.3521x - 0.6474	0.9815	100-20000	19.88	60.25
decanoic acid	y = 0.1909x - 0.0608	0.9970	100-15000	28.36	85.93
dodecanoic acid	y = 0.0104x - 0.0432	0.9958	100-100000	29.43	89.18
hexanoic acid	y = 10.307x - 11.639	0.9946	100-50000	29.79	90.27
nonanoic acid	y = 0.3258x + 0.4660	0.9917	500-20000	52.34	158.61
octanoic acid	y = 0.9802x - 32.759	0.9932	500-600000	62.52	189.46
pentanoic acid	y = 5.2787x - 1.1481	0.9923	100-4000	32.69	99.06
propanoic acid	y = 3.0433x - 1.1553	0.9983	200-200000	32.40	98.19
Alcohols					
1-decanol	y = 0.5110x - 0.2289	0.9974	20-20000	6.59	19.97
1-octanol	y = 0.0131x - 0.0013	0.9994	20-30000	5.52	14.74
1-pentanol	y = 0.0131x - 0.0007	0.9864	20-30000	32.69	99.06
2,3-butanediol	y = 0.0028x - 0.0095	0.9896	50-60000	16.28	49.33
2-phenylethanol	y = 0.2365x - 0.6345	0.9939	50-100000	14.74	44.65
Aldehydes					
2-methylbutanal	y = 0.1838x + 0.0096	0.9959	50-8000	12.75	38.63
3-methylbutanal	y = 0.3801x - 0.1340	0.9919	50-10000	14.22	43.08
benzaldehyde	y = 5.2134x + 0.1572	0.9985	20-10000	6.34	19.22
heptanal	y = 0.5015x + 0.1949	0.9947	50-4000	6.51	19.73
hexanal	y = 0.1580x - 0.0419	0.9800	50-4000	13.30	40.31
nonanal	y = 0.3373x - 0.0223	0.9985	50-4000	15.08	45.70
phenylacetaldehyde	y = 1.1146x - 0.0789	0.9837	50-1000	15.72	47.63
Esters					
ethyl lactate	y = 2.3490x - 0.3693	0.9936	20-4000	6.49	19.67
ethyl octanoate	y = 1.0980x + 0.0815	0.9997	20-50000	6.37	19.31
methyl decanoate	y = 1.2376x + 0.1660	0.9916	20-500	4.75	14.39
methyl octanoate	y = 0.3787x + 0.0677	0.9942	20-4000	5.47	16.57
methyl salicylate	y = 0.7899x - 0.4502	0.9865	20-16950	6.22	18.85
Furan					
2-pentylfuran	y = 0.2469x - 0.0249	0.9971	20-5000	5.82	17.65
Hydrocarbons					
d-limonene	y = 0.8723x - 0.0249	0.9979	20-1000	4.54	13.76
p-xylene	y = 4.8848x + 0.2348	0.9954	20-200	2.99	9.06
o-xylene	y = 0.8222x - 0.0165	0.9914	20-200	6.16	18.67
Indole					
indole	y = 0.8740x + 0.0615	0.9946	50-5000	15.80	47.89
Ketones					

2-decanone	y = 25.7400x + 0.0105	0.9910	5-327	1.20	3.64
2-heptanone	y = 45.4820x - 0.0090	0.9940	5-100	1.55	4.69
2-nonanone	y = 64.1470x + 0.3617	0.9887	5-100	1.20	3.63
acetophenone	y = 19.3070x - 0.6988	0.9937	5-600	1.03	3.22
Lactones					
γ-butyrolactone	y = 28.3930x - 0.7810	0.9911	5-1000	1.56	4.73
γ-nonalactone	y = 0.6809x - 0.0596	0.9913	5-3000	1.65	5.00
Phenols					
2-methoxyphenol	y = 3.4500x - 0.0951	0.9979	5-2000	1.64	4.97
4-methylphenol	y = 22.7050x + 0.0779	0.9935	5-200	1.48	4.47
phenol	y = 27.9180x - 0.4885	0.9864	5-400	1.08	3.27
Pyrazines					
2,3-dimethylpyrazine	y = 0.5162x - 0.0102	0.9997	10-2000	3.02	9.19
2,5-dimethylpyrazine	y = 0.4061x - 0.0009	0.9993	10-4000	2.97	9.00
trimethylpyrazine	y = 0.2463x + 0.0022	0.9974	10-4000	3.11	9.41
Sulfur compounds					
dimethyl sulfone	y = 1.4970x - 0.3116	0.9897	20-5000	6.55	19.84
methional	y = 0.3363x - 0.0043	0.9954	20-500	3.11	9.42

Table S4. Recovery rates of 48 volatile compounds analyzed by the HS-SPME-Arrow-GC/MS in spiked oil matrix

Volatile compounds	Concentration of spiking 1 (ng/g)	Recovery (%)	RSD (%)	Concentration of spiked 2 (ng/g)	Recovery (%)	RSD (%)	Concentration of spiked 3 (ng/g)	Recovery (%)	RSD (%)
Acids									
2-methylbutanoic acid	1206.77	93.2±6.8	7.27	2413.53	100.6±7.7	7.69	4827.06	106.1±7.3	6.9
2-methylpropanoic acid	994.42	104.9±4.9	4.69	1988.84	102.7±7.9	7.65	3977.69	101.3±5.9	5.9
3-methylbutanoic acid	916.73	98.3±8.5	8.65	1833.45	97.5±6.3	6.41	3666.90	100.5±8.1	8.0
acetic acid	9538.04	92.8±8.9	9.55	19076.08	102.5±9.0	8.78	38152.15	102.7±8.9	9.7
butanoic acid	2658.27	94.8±7.3	7.65	5316.53	90.1±3.0	3.32	10633.06	103.0±6.9	6.7
decanoic acid	3581.63	102.5±7.8	7.62	7163.26	99.5±5.7	5.71	14326.52	93.0±8.2	8.8
dodecanoic acid	6096.15	107.6±8.9	8.25	12192.31	105.0±3.5	3.37	24384.62	107.2±4.0	3.8
hexanoic acid	940.41	104.4±6.2	5.89	1880.83	103.0±6.3	6.13	3761.65	94.0±7.4	7.9
nonanoic acid	1976.57	96.2±7.5	7.73	3953.14	101.3±9.7	9.58	7906.28	100.7±6.8	6.7
octanoic acid	23230.96	110.0±0.9	0.77	46461.92	97.2±9.5	9.72	92923.84	102.0±8.0	7.8
pentanoic acid	195.40	107.6±3.0	2.76	390.80	106.8±6.1	5.74	781.61	103.4±4.7	4.6
propanoic acid	727.60	90.5±2.0	2.21	1455.21	99.7±7.5	7.54	2910.42	102.1±3.7	3.6
Alcohols									
1-decanol	2415.75	90.4±8.2	9.0	4831.51	90.5±3.3	3.6	9663.01	92.3±4.2	4.5
1-octanol	7456.74	104.7±9.6	9.2	14913.49	103.8±9.7	9.3	29826.97	97.3±7.3	7.5
1-pentanol	6070.76	105.2±3.9	3.7	12141.51	91.2±0.8	0.9	24283.02	99.5±7.4	7.4
2,3-butanediol	13592.33	107.3±6.5	6.0	27184.66	104.3±7.7	7.4	54369.31	91.0±7.3	8.0
2-phenylethanol	2443.04	110.0±0.0	0.0	4886.08	101.4±8.5	8.4	9772.17	100.0±8.7	8.7
Aldehydes									
2-methylbutanal	985.99	91.6±6.3	6.9	1971.98	101.3±8.2	8.1	3943.95	98.5±4.8	4.1
3-methylbutanal	768.16	108.2±4.0	3.7	1536.33	100.7±9.3	9.2	3072.65	94.2±8.5	9.0
benzaldehyde	190.96	101.1±5.7	5.7	381.93	99.3±5.3	5.3	763.85	104.9±5.8	5.5
heptanal	606.87	99.7±1.9	1.9	1213.73	101.2±7.0	6.9	2427.46	98.3±5.6	5.7
hexanal	311.92	100.3±9.0	9.0	623.84	93.6±8.1	8.6	1247.68	99.5±7.6	7.6
nonanal	215.88	98.7±8.0	8.1	431.76	99.4±8.7	8.8	863.52	94.9±9.4	9.9
phenylacetaldehyde	69.37	109.7±0.5	0.5	138.75	106.6±3.0	2.8	277.50	91.4±4.1	4.5
Esters									
ethyl lactate	441.88	99.1±6.1	6.1	883.77	103.7±9.1	8.8	1767.53	96.0±1.3	1.3
ethyl octanoate	9822.47	96.9±6.7	6.9	19644.93	95.8±9.4	9.8	39289.86	96.6±1.5	1.5
methyl decanoate	79.89	95.5±7.8	8.1	159.78	94.9±4.2	4.5	319.56	105.4±7.5	7.1
methyl octanoate	548.76	98.8±7.5	7.6	1097.53	101.4±8.0	7.9	2195.05	96.78±6.8	7.0
methyl salicylate	3525.89	102.9±9.4	9.2	7051.78	103.4±7.1	6.88	14103.56	95.31±7.3	7.7
Furan									
2-pentylfuran	165.18	98.6±1.4	1.5	330.36	97.4±2.4	2.4	660.73	94.2±9.8	10.4
Hydrocarbons									

d-limonene	26.28	90.9±0.3	0.4	52.56	107.07±9.5	8.9	105.11	95.3±4.6	4.8
p-xylene	12.27	93.5±3.2	3.4	24.54	99.4±9.8	10.0	49.07	93.9±3.1	3.3
o-xylene	21.04	104.3±8.3	7.9	42.08	102.0±7.0	6.9	84.17	95.1±8.1	8.5
Indole									
indole	1064.00	101.5±2.5	2.5	2127.99	101.7±2.9	2.9	4255.99	108.4±8.9	8.2
Ketones									
2-decanone	72.19	103.4±7.2	7.0	144.37	92.2±3.3	3.6	288.75	97.3±7.3	7.5
2-heptanone	9.29	100.5±5.1	5.1	18.59	91.4±4.7	5.1	37.17	94.6±6.5	6.9
2-nonanone	11.94	105.9±8.0	7.5	23.89	97.2±7.4	7.7	47.78	108.4±8.6	8.0
acetophenone	35.19	109.9±2.7	2.4	70.38	94.8±7.2	7.6	140.76	100.2±9.0	9.0
Lactones									
γ-butyrolactone	39.99	92.6±7.0	7.5	79.98	95.8±7.6	8.0	159.97	101.3±9.0	8.9
γ-nonalactone	746.27	99.7±8.7	8.7	1492.53	108.0±4.5	4.2	2985.07	101.6±8.3	8.2
Phenols									
2-methoxyphenol	28.89	108.4±1.4	1.3	57.77	94.6±1.3	1.4	115.55	101.3±9.0	8.9
4-methylphenol	18.25	105.8±5.2	4.9	36.49	92.9±6.5	7.0	72.99	99.5±8.6	8.6
phenol	32.93	92.8±5.4	5.8	65.85	90.0±5.0	5.5	131.71	91.4±2.8	3.1
Pyrazines									
2,3-dimethylpyrazine	31.62	106.7±4.2	3.9	63.24	101.0±7.9	7.8	126.48	90.3±4.2	4.6
2,5-dimethylpyrazine	912.21	91.7±6.5	7.1	1824.43	94.0±7.4	7.9	3648.85	97.8±8.1	8.3
trimethylpyrazine	245.91	92.5±8.8	9.5	491.81	94.0±6.2	6.6	983.62	90.9±4.1	4.6
Sulfur compounds									
dimethyl sulfone	548.74	101.8±8.9	8.7	1097.49	103.9±6.6	6.4	2194.97	95.2±4.9	5.2
methional	52.76	109.0±4.4	4.0	105.52	98.7±8.0	8.1	211.04	98.2±8.7	8.9

3.5. Volatile profiles of edible insect oils according to roasting

This study provides a comparative analysis of the volatile compounds in roasted and unroasted insect oils. Volatile compounds were analyzed using HS-SPME-Arrow-GC/MS, and the results are presented in Table 3. A total of 48 volatile compounds were detected in the oils extracted from the edible insects. The volatile compounds were classified into 12 groups: acids (12), alcohols (5), aldehydes (7), esters (5), furan (1), hydrocarbons (3), indole (1), ketones (4), lactones (2), phenols (3), pyrazines (3), and sulfur compounds (2). UT, UG, UL, UZ, and UP contained 23, 30, 24, 28, and 27 volatile compounds, respectively. In contrast, RT, RG, RL, RZ, and RP samples contained 38, 36, 32, 42, and 34 volatile compounds, respectively. The number of volatile compounds detected in roasted insect oils was higher than that detected in unroasted oils. The greatest difference in volatile compound composition was observed in *T. molitor* oil, with an increase of 15 compounds, such as aldehydes, ketones, furan and pyrazines. These differences are attributed to chemical modification, such as the Maillard reaction, lipid degradation, and caramelization, which are known to generate various volatile compounds during roasting (Mansouri et al., 2023). Overall, the roasting altered the volatile profile of the oil extracted from edible insects.

Among the pyrazines known to key contributors to the volatile profile, 2,3-dimethylpyrazine, 2,5-dimethylpyrazine, and trimethylpyrazine were identified. Roasted oils contained a greater variety and higher total concentrations of pyrazines than unroasted oils. 2,5-dimethylpyrazine, associated with burnt, cocoa, and coffee notes, was the most abundant pyrazine with the highest concentration in RT (2399.0 ng/g). Additionally, 2,3-dimethylpyrazine and trimethylpyrazine were found only in the roasted oil. Three pyrazines have been detected in different oils, including roasted rapeseed and flaxseed (Gao et al., 2024; Suri et al., 2020). Moreover, these compounds contribute to the cocoa, coffee, and caramel notes in roasted foods, which are important for increasing consumer acceptance (Yin et al., 2021).

Pyrazines are generated via the Maillard reaction that occurs during various

processing methods. The formation process begins with the reaction of reducing sugars and amino acids to produce N-glucosamine and N-fructosylamine. These intermediates are transformed via Amadori rearrangement and enolization to form deoxyhexosones, leading to the formation of lipid oxidation products (α-dicarbonyl or α-hydroxycarbonyl compounds) (Hu et al., 2024). During the Strecker degradation, lipid oxidation products react with amino acids, leading to the release of NH_2, CO_2, and H_2O, and resulting in the formation of α-aminoketones (Lee, Lee et al., 2023). Through dehydration and dimerization, these α-aminoketones are converted into pyrazine derivatives (Fig. 2a) (Lee, Lee et al., 2023; Ma et al., 2024; Yu et al., 2021)

In the edible insect oils, a furan compound, identified as 2-pentylfuran, provides butter, floral, and fruity notes. 2-Pentylfuran has a low sensory threshold and primarily contributes to the sensory characteristics of roasted foods (Perez-Santaescolastica et al., 2023; Zhang et al., 2022). Notably, this compound was identified only in roasted samples. Furans are formed via the oxidation of linoleic acid during heating (Cha and Lee, 2020). Linoleic acid undergoes lipid oxidation during roasting, leading to the formation of hydroperoxides at C9 position. During the degradation process, it generates 3-nonenal, which interacts with reactive oxygen species to produce hydrogen peroxide. Subsequently, the C5 compounds and lipid hydroperoxides (ROOH) generate alkyl radicals that undergo isomerization and cyclization to form 2-pentylfuran (Fig. 2b) (Hu et al., 2024; Ma et al., 2024).

According to Perez-Santaescolastica et al. (2023), acid compounds are primarily produced through microbial metabolism and the oxidation of aldehydes involved in the Strecker degradation pathway. The concentrations of acid compounds increased in roasted samples compared to those in unroasted samples. These results are consistent with those of a previous study on sesame oil subjected to the Maillard reaction (Hu et al., 2024). Acetic acid was detected in all samples and was identified as the predominant acid in *T. molitor* and *G. bimaculatus* oils ($p < 0.05$). Lee et al. (2023) reported that acetic acid was a major volatile compound in edible

insect oil. Furthermore, octanoic acid was detected at the highest concentrations in *G. bimaculatus* and *Z. atratus* oils, which imparted cheese and fat notes.

In general, alcohol exhibits intense sensory attributes and contributes to sweetness, fruity, and sulfurous notes (Lee et al., 2019). The total alcohol content in oils was higher in roasted samples than in unroasted samples, with RP exhibited the highest proportion of alcohol compounds at 51.3 %. 1-Pentanol, which imparts almond and fruity notes, was detected only in the RL. Similarly, 1-octanol was detected exclusively at RT. 2,3-Butanediol was identified in all samples and contributed to the cream, floral, and fruity notes. Notably, its concentration was significantly higher in RG (58021.1 ng/g) and RP (59418.1 ng/g) than in UG and UP. 2-Phenylethanol increased in RG (93386.1 ng/g) compared with UG (87125.8 ng/g). 2-Phenylethanol, a major volatile compound identified in *G. bimaculatus*, imparts characteristic cornflake, floral, and honey notes.

As carbonyl compounds, aldehydes impart green, fruity, and fatty notes (Hu et al., 2024; Zhang et al., 2022). In total, seven aldehydes were detected, with 2-methylbutanal, 3-methylbutanal, and heptanal found only in roasted oils. 2-methylbutanal and 3-methylbutanal are formed via Strecker degradation during roasting (Yin et al., 2021; Zhang et al., 2022), and contribute to almond, chocolate, and fruit notes. These compounds were most concentrated in RT, reaching 2903.88 ng/g and 2878.2 ng/g, respectively ($p < 0.05$). These compounds have been reported to be detected only in roasted sesame oil, with no detection in unroasted sesame oil. (Yin et al., 2021). Benzaldehyde, which impart almond and berry notes, is generated through the Maillard reaction pathway (Lee, Lee et al., 2023) and was identified at significantly higher levels in RG (440.4 ng/g) and RP (483.9 ng/g) ($p < 0.05$). The concentration of benzaldehyde was higher in the roasted samples than in the unroasted samples. Similarly, benzaldehyde levels were higher in roasted rapeseed oil than in unroasted oil (Gao et al., 2024). Hexanal is produced by the oxidation of linoleic acid, whereas nonanal is produced by the oxidation of oleic acid (Yin et al., 2021). Hexanal was detected at the highest level in *L. migratoria* oils, whereas nonanal was the most abundant in *G. bimaculatus* oils. Although

hexanal and nonanal are considered undesirable volatile compounds, they possess relatively high odor thresholds (Neugebauer et al., 2020). Therefore, their increased levels are unlikely to significantly influence the overall aroma profile.

The esterification reaction between alcohol and carboxylic acid leads to the formation of esters (Chen et al., 2024), also increased following roasting. Ethyl octanoate, which contributes to apricot, banana, and brandy notes, was present at higher levels in roasted samples than in unroasted samples. Particularly, ethyl octanoate was detected at high concentrations in *Z. atratus* oils, which is attributed to the elevated levels of octanoic acid. Perez-Santaescolastica et al. (2023) reported that ethyl octanoate is a major volatile compound in *Z. atratus*. Methyl salicylate, which provides almonds, caramels, and fresh notes, was identified in all samples. The RL sample demonstrated a significantly higher result of 8170.1 ng/g ($p < 0.05$).

Among hydrocarbon compounds, d-limonene, imparts citrus and mint notes, was detected in all insect oils. It was abundant in *T. molitor* and *P. brevitarsis*, consistent with previous studies (Cha et al., 2024; Nam et al., 2025). Especially, its content was significantly higher in roasted samples ($p < 0.05$). D-limonene has demonstrated antimicrobial activity against various fungal and bacterial strains, including pathogens (Han et al., 2024), potentially enhancing the functional quality of edible insect oils.

Sulfur compounds are essential component to the volatile profile and contribute to the sensory characteristics associated with onion and cooked potato notes (Zhang et al., 2022). These compounds are generated via the Maillard reaction from sulfur-containing amino acids (Gao et al., 2024). Dimethyl sulfone contributes to the burnt and sulfurous notes. This compound was detected at the highest levels in RG and RL (2466.5 ng/g and 2264.8 ng/g). Methional, which imparts baked potato and caramel notes, was found only in two roasted samples (RT and RZ). The roasted oils contained significantly higher levels of these two sulfur compounds than the unroasted oils ($p <0.05$).

Two lactone compounds were detected. ɣ-Butyrolactone, a volatile compound also

identified in passion fruit seed oil (Zheng et al., 2024), was detected in all samples except for UT, and showed the highest concentration in RG ($p < 0.05$). This compound contributes to the caramel, cheese, fruit notes. In contrast, γ-nonalactone, which imparts apricot, cocoa, and coconut notes, was detected in all insect oils, except *Z. atratus*.

Ketones, though present in smaller quantities, are typically formed through thermal oxidation of unsaturated fatty acids (Giri et al., 2010). Acetophenone was the most abundant ketone identified, which imparts almond, animal, and floral notes and was found in all samples except *L. migratoria* oils. Three compounds were detected in phenol groups. Among them, 2-methoxyphenol, a primary volatile compound in sesame oil with a smoked note (Yin et al., 2021), was found at the highest concentration in RL (1417.9 ng/g) ($p < 0.05$). Phenol, known for its medicinal and clove notes, is considered an unfavorable volatile compound in foods such as wine and fruit juice (Leonard et al., 2023), and was detected for all samples in this study. Indole was identified only in *G. bimaculatus* and *Z. atratus* oils. This compound reported as a key unfavorable volatile compound for its muddy and animal notes in fish and Chinese *Baijiu* (Chen et al., 2023; Gong et al., 2024).

Table 3. Concentrations (ng/g) of volatile compounds identified in oils extracted from roasted and unroasted edible insects

Compounds	UT	RT	UG	RG	UL	RL	UZ	RZ	UP	RP
Acids										
2-methylbutanoic acid	316.3±1.8^{f}	2923.7±68.1^{b}	7769.9±329.1^{a}	7847.4±547.3^{a}	1189.1±121.6^{d}	2963.8±322.9^{b}	617.0±40.3^{e,f}	2413.5±98.8^{c}	660.7±30.6^{e,f}	842.7±57.2^{d,e}
2-methylpropanoic acid	3194.7±385.2^{b}	4586.5±622.1^{a}	1055.6±135.4^{d,e}	1691.8±20.0^{c}	384.6±64.4^{f,g}	3157.5±412.6^{b}	214.6±33.2^{g}	1988.8±219.1^{c}	740.5±51.2^{e,f}	1518.7±30.6^{c,d}
3-methylbutanoic acid	4227.5±267.2^{c,d}	3545.2±367.1^{d}	11084.6±135.0^{b}	16246.7±1564.9^{a}	1447.8±247.3^{e}	5079.0±74.6^{c}	551.9±80.3^{f}	1833.5±121.5^{e}	273.0±18.5^{f}	338.3±33.7^{f}
acetic acid	41925.9±422.6^{d}	90631.6±3391.8^{b}	71232.6±4060.8^{c}	109039.4±4845.0^{a}	1363.2±132.4^{g}	2344.0±222.4^{g}	10185.6±353.0^{f}	19076.1±540.3^{e}	3859.4±236.3^{g}	5051.7±256.9^{g}
butanoic acid	712.2±119.4^{e,f}	1730.0±17.8^{e}	14200.5±1989.0^{b}	18759.1±222.6^{a}	1082.1±71.8^{e,f}	3378.2±117.9^{d}	415.88±34.58^{f}	5316.5±183.6^{c}	229.9±1.7^{f}	375.1±29.8^{f}
decanoic acid	1167.7±133.6^{c}	1331.2±80.0^{c}	nd	nd	nd	nd	2937.7±366.7^{b}	7163.3±60.5^{a}	337.7±6.1^{d}	391.2±5.5^{d}
dodecanoic acid	954.8±94.1^{b}	12192.3±1665.4^{a}	nd	nd	nd	nd	nd	nd	nd	nd
hexanoic acid	1913.5±11.2^{d}	1963.9±43.7^{d}	2174.2±94.5^{c}	2123.3±119.6^{c}	3158.3±103.7^{b}	5367.5±144.8^{a}	1525.7±47.8^{e}	1880.8±49.2^{d}	nd	nd
nonanoic acid	2868.6±221.3^{c}	5498.1±614.9^{a}	1333.3±117.5^{e}	3566.0±373.6^{b}	nd	nd	1858.0±78.8^{d}	3953.1±145.1^{b}	625.5±18.0^{f}	1001.7±115.7^{e,f}
octanoic acid	34253.9±86.8^{f}	36889.0±667.9^{e}	33595.3±18.7^{f}	65081.3±2361.6^{a}	44932.0±1050.9^{c}	51577.5±1076.6^{b}	42294.9±167.2^{d}	46461.9±626.4^{c}	33607.8±46.0^{f}	34129.3±73.7^{f}
pentanoic acid	nd	nd	1870.6±109.6^{c}	2800.6±164.4^{b}	1959.7±44.4^{c}	3707.0±115.7^{a}	nd	390.8±12.2^{d}	234.6±5.0^{e}	321.1±20.3^{d,e}
propanoic acid	1151.8±57.6^{d}	2202.2±94.3^{d}	96765.1±8777.3^{b}	115139.8±5736.3^{a}	1890.3±76.2^{c}	37955.0±3918.9^{c}	841.8±82.2^{d}	1455.2±74.7^{a}	1104.3±45.0	1853.9±101.0^{d}
Alcohols										
1-decanol	nd	nd	nd	nd	nd	nd	1165.5±59.8^{b}	4831.5±549.0^{a}	nd	nd
1-octanol	nd	14913.49±184.7^{a}	nd	nd	nd	nd	nd	nd	nd	nd
1-pentanol	nd	nd	nd	nd	nd	12141.5±434.0^{a}	nd	nd	nd	nd
2,3-butanediol	11220.2±217.4^{e}	15297.6±2062.0^{e}	46013.0±4972.6^{b}	58021.1±2548.9^{a}	15114.9±677.0^{e}	26438.5±1721.5^{d}	27107.7±1892.8^{d}	27184.7±1843.5^{d}	32276.9±2326.8^{c}	59418.1±4109.6^{a}
2-phenylethanol	nd	nd	87125.8±3505.6^{b}	93386.1±1506.0^{a}	nd	nd	2795.6±48.8^{c}	4886.1±25.8^{c}	3105.7±42.3^{c}	3697.7±223.7^{c}
Aldehydes										
2-methylbutanal	nd	2903.9±362.3^{a}	nd	1702.8±106.3^{c}	nd	548.5±54.5^{d}	nd	1972.0±92.6^{b}	nd	2142.2±136.9^{b}
3-methylbutanal	nd	2878.2±120.6^{a}	nd	1821.0±96.7^{b}	nd	657.6±15.2^{e}	nd	1536.3±45.5^{c}	nd	1179.0±13.7^{d}
benzaldehyde	21.8±1.0^{f}	87.2±6.8^{d}	71.8±5.5^{d,e}	440.4±33.2^{a}	27.1±2.2^{e,f}	383.8±36.0^{b}	21.3±2.2^{f}	381.9±37.2^{b}	261.1±35.4^{c}	483.9±46.2^{a}

heptanal	nd	29.6±3.2^{b}	nd	nd	nd	nd	nd	1213.7±10.2^{a}	nd	nd
hexanal	280.0±3.7^{e}	345.3±3.1^{e}	745.9±76.5^{d}	1248.5±106.0^{c}	2749.8±374.5^{b}	3744.0±126.6^{a}	348.1±13.9^{e}	623.8±36.5^{d}	nd	nd
nonanal	100.2±3.6^{f}	158.3±24.9^{f}	1149.3±53.7^{c}	2858.9±208.1^{a}	431.8±34.2^{e}	537.8±43.1^{d,e}	115.5±17.1^{f}	431.7±34.2^{e}	619.1±45.2^{d}	2447.8±190.6^{b}
phenylacetaldehyde	80.4±1.7^{c}	87.4±0.8^{b}	nd	nd	nd	nd	nd	138.8±0.8^{a}	nd	nd
Esters										
ethyl lactate	nd	nd	nd	nd	nd	nd	635.9±35.2^{d}	883.8±115.8^{c}	1332.2±78.8$_{b}$	1641.5±123.1^{a}
ethyl octanoate	57.2±0.8^{e}	76.69±1.35^{e}	12960.5±861.7^{d}	15443.5±367.6^{c}	52.1±2.0^{e}	101.9±5.3^{e}	18747.3±229.9^{b}	19644.9±377.9^{a}	nd	nd
methyl decanoate	nd	nd	nd	nd	nd	nd	50.4±2.4^{b}	159.8±12.9^{a}	nd	nd
methyl octanoate	nd	nd	nd	nd	nd	nd	200.2±6.4^{b}	1097.5±119.1^{a}	nd	nd
methyl salicylate	764.1±14.6^{f}	828.0±10.2^{f}	1253.6±65.8^{f}	4414.3±558.4^{e}	5308.9±487.8^{d}	8170.1±343.8^{a}	6148.7±662.0^{c}	7051.8±318.0^{b}	674.6±7.9^{f}	754.1±24.5^{f}
Furan										
2-pentylfuran	nd	3138.5±316.3^{a}	nd	783.1±3.3^{c}	nd	1086.4±46.8$_{b}$	nd	330.4±23.4^{d}	nd	144.9±1.5^{e}
Hydrocarbons										
d-limonene	211.4±16.3^{d}	415.5±14.4^{b}	nd	247.7±20.9^{c}	63.8±5.4^{e}	52.4±1.0^{e}	nd	52.6±5.4^{e}	222.2±19.6^{d}	473.8±15.0^{a}
p-xylene	nd	45.7±1.1^{e}	51.2±0.9^{d}	42.0±3.1^{f}	79.5±0.3^{b}	17.0±1.0^{h}	nd	24.5±1.4^{g}	74.5±0.8^{c}	86.7±1.4^{a}
o-xylene	nd	45.0±1.0^{d,e}	45.6±1.2^{d,e}	169.8±24.1^{a}	74.9±6.1^{b,c}	89.0±7.0^{b}	nd	42.1±1.3^{e}	60.6±7.0^{c,d}	78.9±8.9^{b}
Indole										
indole	nd	nd	777.4±110.6^{c}	1885.5±133.1^{b}	nd	nd	1920.5±252.5^{b}	2128.0±112.5^{a}	nd	nd
Ketones										
2-decanone	nd	84.8±12.4^{b}	30.1±1.3^{c}	72.8±5.4^{b}	nd	nd	nd	nd	nd	144.4±20.5^{a}
2-heptanone	9.5±0.2^{b,c}	8.8±0.2^{b,c}	5.6±0.7^{d}	19.6±1.6^{a}	8.5±0.3^{c}	9.8±0.1^{b}	nd	18.6±0.8^{a}	nd	nd
2-nonanone	nd	20.2±2.5^{d}	11.0±1.4^{e}	27.0±3.9^{b}	nd	5.2±0.6^{f}	nd	23.9±0.8^{c}	6.9±0.4^{f}	33.2±1.9^{a}
acetophenone	nd	106.8±13.2^{e}	273.7±31.0^{d}	443.8±6.1^{c}	nd	nd	40.2±0.3^{g}	70.4±4.1^{f}	481.3±13.9^{b}	674.5±16.7^{a}
Lactones										
γ-butyrolactone	nd	109.3±0.5^{c}	129.5±2.7^{b}	489.0±9.7^{a}	44.8±2.2^{g}	130.9±7.4^{b}	66.3±1.9^{e}	80.0±5.0^{d}	38.9±0.1^{g}	56.3±1.8^{f}
γ-nonalactone	nd	175.7±25.4^{c,d}	191.6±10.8^{c}	147.5±7.7^{d}	283.4±44.9^{b}	1492.5±37.0^{a}	nd	nd	nd	170.8±17.0^{c,d}
Phenols										
2-methoxyphenol	nd	nd	216.8±8.9^{d,e}	472.0±7.8^{b}	378.7±2.6^{c}	1417.9±128.6^{a}	48.3±0.1^{f}	57.8±1.5^{f}	157.1±6.1^{e}	284.0±22.0^{d}
4-methylphenol	nd	nd	nd	nd	nd	nd	nd	nd	34.77±4.0^{a}	36.5±1.6^{a}

phenol	28.0±0.1^{g}	18.3±0.1^{g}	76.4±3.6^{d,e}	110.8±7.6^{c}	71.2±8.1^{d,e,f}	85.2±2.2^{d}	57.5±5.7^{f}	65.9±7.8^{e,f}	216.2±11.5^{b}	357.5±15.8^{a}
Pyrazines										
2,3-dimethylpyrazine	nd	100.6±5.7^{b}	nd	83.4±3.1^{c}	nd	123.1±11.2^{a}	Nd	63.2±0.5^{d}	nd	41.9±2.3^{e}
2,5-dimethylpyrazine	232.6±3.8^{f}	2399.0±148.4^{a}	67.2±3.6^{g,h}	1213.0±108.8^{d}	nd	1364.8±79.2^{c}	57.1±5.1 ^{g,h}	1824.4±49.3^{b}	136.2±10.3^{f,g}	784.9±9.5^{e}
trimethylpyrazine	nd	285.2±9.1^{c}	nd	300.2±1.9^{c}	nd	1439.2±164.1^{a}	nd	491.8±46.9^{b}	nd	275.3±40.6^{c}
Sulfur compounds										
dimethyl sulfone	1025.4±2.5^{d}	2033.8±191.8^{c}	1997.6±106.6^{c}	2466.5±90.8^{a}	775.9±57.9^{e}	2264.8±69.8^{b}	637.0±7.9^{e}	1097.5±20.0^{d}	1108.2±114.2^{d}	1860.3±177.5^{c}
methional	nd	155.1±11.1^{a}	nd	nd	nd	nd	nd	105.5±0.1^{b}	nd	nd

UT, Unroasted *Tenebrio molitor* oil; RT, Roasted *Tenebrio molitor* oil; UG, Unroasted *Gryllus bimaculatus* oil; RG, Roasted *Gryllus bimaculatus* oil; UL, Unroasted *Locusta migratoria* oil; RL, Roasted *Locusta migratoria* oil; UZ, Unroasted *Zophobas atratus*; RZ, Roasted *Zophobas atratus* oil; UP, Unroasted *Protaetia brevitarsis* oil; RP, Roasted *Protaetia brevitarsis* oil; All results are expressed as the mean ± standard deviation of three replicates (n = 3); $^{a-h}$ values in row with different letters are significantly different as $p < 0.05$ according to Duncan's multiple range test; nd: not detected.

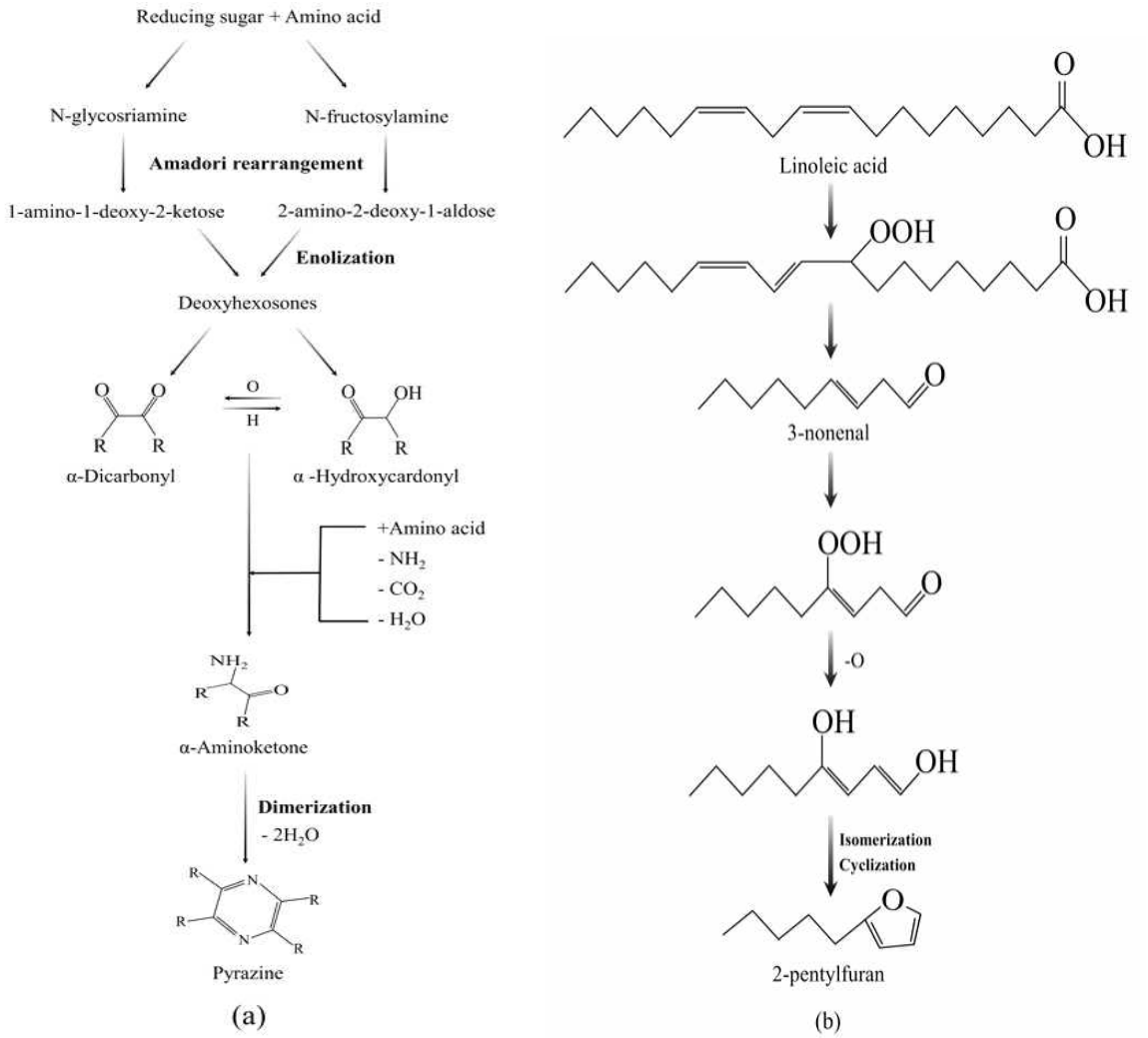

Figure. 2. Formation mechanism of key volatile compounds in roasted edible insect oils via the Maillard reaction. (a) formation pathway of pyrazine compounds, and (b) 2-pentylfuran

3.6. Heatmap analysis of volatile compounds in edible insect oils

To further elucidate the differences in volatile profiles between roasted and unroasted edible insect oils, heatmap analysis was performed (Fig. S1). The heatmap color scale was normalized from a maximum of +2 (dark red) to a minimum of −2 (dark blue), indicating the relative levels of volatile compounds from high to low. Distinct red patterns were observed in RT for 2-methylbutanal, 3-methylbutanal, 2,5-dimethylpyrazine, 2-pentylfuran, and methional commonly generated by Strecker degradation. d-limonene, which provides a citrus and mint notes, exhibited a more pronounced red pattern in the roasted samples (RT and RP). Moreover, 2,3-dimethylpyrazine and trimethylpyrazine, which impart caramel, cocoa, and cotton candy notes, exhibited the most intense red patterns in RL. γ-butyrolactone was most abundant in RG, while γ-nonalactone showed the highest concentration in RL. Additionally, hexanal generated through lipid oxidation was distinguished by red patterns in the RL. Nonanal and acetic acid exhibited the most intense red patterns in RG. Phenol, an unfavorable volatile compound, showed the highest concentration in *P. brevitarsis*, whereas indole exhibited a red pattern in *Z. atratus*. Although the levels of some unfavorable volatile compounds also increased in the roasted oils, they are not expected to compromise the oil quality because these compounds possess high odor thresholds (Neugebauer et al., 2020). Overall, the heatmap clearly demonstrated that roasting enhanced the formation of favorable compounds in roasted oils compared with unroasted oils.

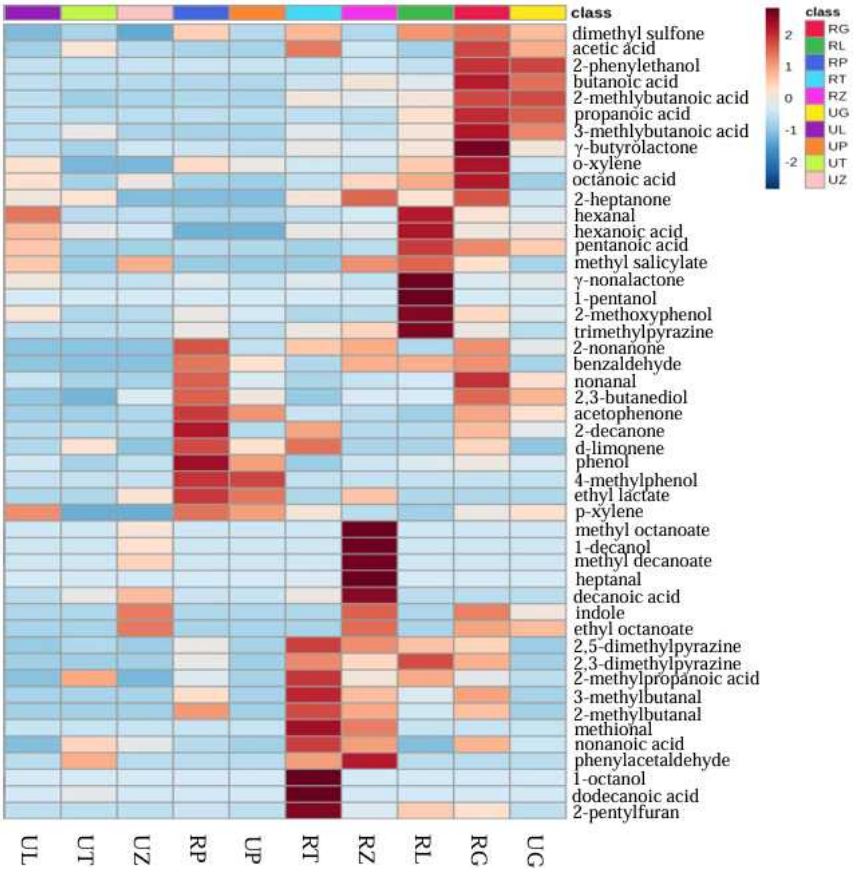

Figure S1. Heatmap of changes in volatile compound in roasted and unroasted edible insect oils from five species. UT, Unroasted *Tenebrio molitor* oil; RT, Roasted *Tenebrio molitor* oil; UG, Unroasted *Gryllus bimaculatus* oil; RG, Roasted *Gryllus bimaculatus* oil; UL, Unroasted *Locusta migratoria* oil; RL, Roasted *Locusta migratoria* oil; UZ, Unroasted *Zophobas atratus* oil; RZ, Roasted *Zophobas atratus* oil; UP, Unroasted *Protaetia brevitarsis* oil; RP, Roasted *Protaetia brevitarsis* oil

3.7. Sensory profiles of unroasted and roasted insect oils

ANOVA results showed that both insect species and the interaction between species and roasting significant influenced odor liking and intensity scores ($p < 0.05$). Although roasting significantly influenced odor preference ($p < 0.05$), its effect on odor intensity was not significant ($p > 0.05$).

The odor liking and intensity scores for each sample are presented in Fig. 3. Roasting led to an increase in odor liking scores across all species, with statistically significant differences observed for all species except L. *migratoria* ($p < 0.05$). Notably, *P. brevitarsis*, which had the lowest liking score before roasting, achieved a similar rating to *G. bimaculatus* and *L. migratoria* after roasting (Fig. 3a). In contrast, the odor intensity remained unchanged before and after roasting for *T. molitor*, *Z. atratus*, and *G. bimaculatus* samples, whereas a decrease was observed for *L. migratoria* and *P. brevitarsis* samples (Fig. 3b). These findings indicate that roasting generally enhanced odor liking but had inconsistent effect on odor intensity.

In the Correspondence analysis (CA) of the sensory profiles is shown in Fig. 4. A 62.42 % of the total variance was explained by Dim 1 (33.21%) and Dim 2 (29.21 %). The HCPC classified the samples into three clusters: Cluster 1 (C1; UG, UT, UP), Cluster 2 (C2; RZ, RT, RP, RG, UZ, RL), and Cluster 3 (C3; UL). The samples in C1 were positioned in Dim 1 (+), characterized by descriptors such as sour, rotten, fishy, ammonia, and dried seafood odors. Conversely, Dim 1 (-) was strongly associated with descriptors such as nutty, toasty, grainy, bread, and baked goods odors, where C2 was located. Among these, UZ formed a cluster with the roasted samples rather than with the unroasted samples, indicating that its sensory characteristics were more similar to those of the roasted samples. No significant differences in odor liking levels were found between UZ and the roasted samples. C3 was positioned in Dim 2 (+), characterized by descriptors such as grassy, raisin, jujube, minty, green tea, and woody odors, and here, exhibiting distinct characteristics compared to the other samples.

Overall, no strong correlation was observed between odor liking and intensity. For T. *molitor*, Z. *atratus*, and G. *bimaculatus*, odor intensity tended to increase after roasting, whereas in L. *migratoria* and P. *brevitarsis*, which exhibited initially stronger and more distinct odors, the intensity slightly decreased after roasting. Nonetheless, in all cases, odor liking improved following roasting. This enhancement is likely due to the formation of pleasant odor notes and the masking of undesirable notes during the roasting. These findings align with the study by (Cha et al., 2024), which suggests that the odor profile is more strongly correlated to consumer acceptance, as demonstrated in the fermentation of *P. brevitarsis* larvae.

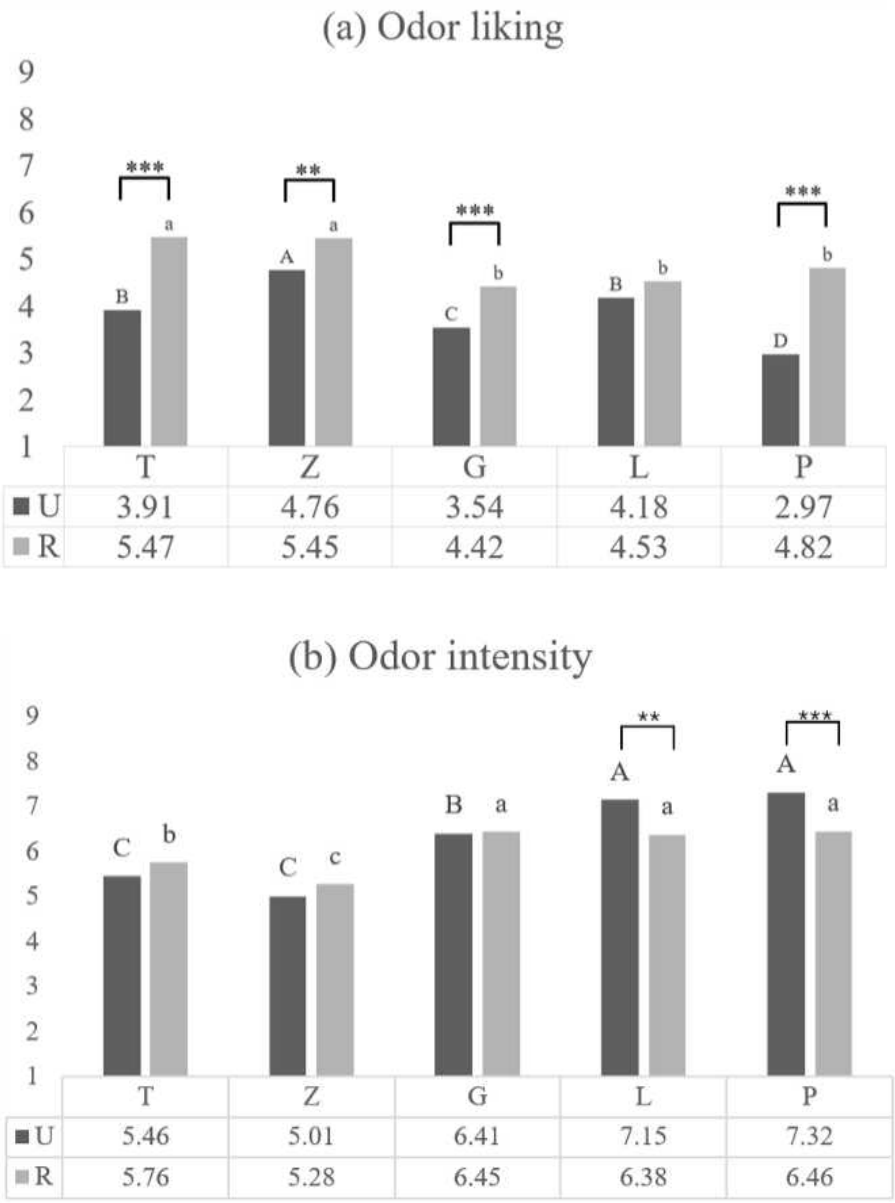

Figure 3. (a) Odor liking and (b) intensity of the roasted and unroasted edible insect oils obtained from five species (*Tenebrio molitor*, *Gryllus bimaculatus*, *Locusta migratoria*, *Zophobas atratus*, and *Protaetia brevitarsis*)

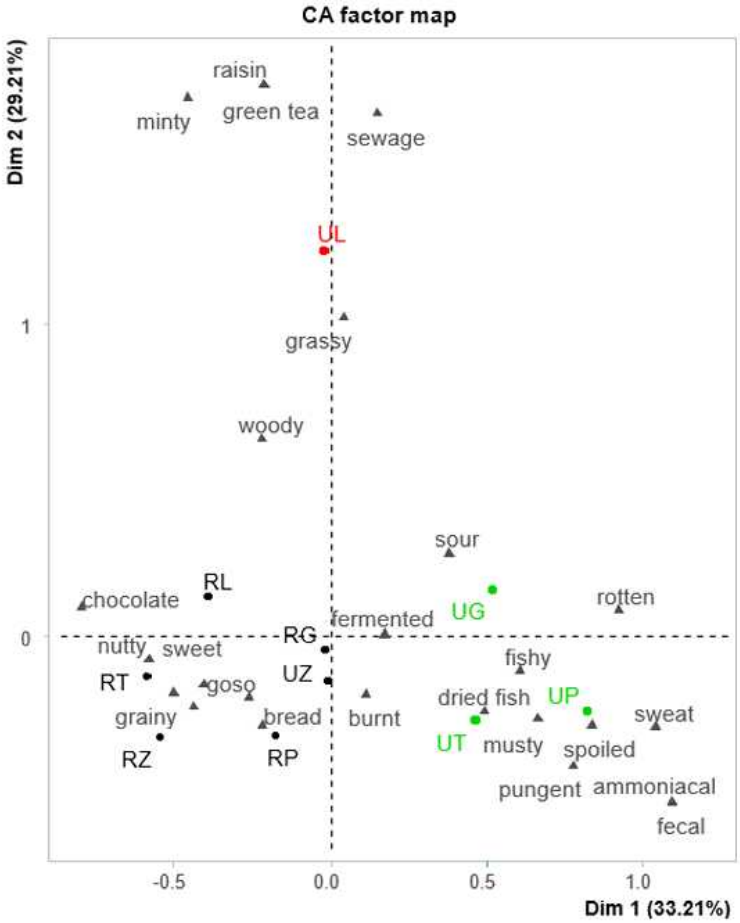

Figure 4. Correspondence analysis plot of the roasted and unroasted edible insect oils obtained from five species (*Tenebrio molitor*, *Gryllus bimaculatus*, *Locusta migratoria*, *Zophobas atratus*, and *Protaetia brevitarsis*)

Ⅳ. CONCLUSION

This study optimized the roasting conditions of edible insects using RSM. Moreover, oils extracted from unroasted and roasted edible insects were evaluated the quality characteristics, volatile profiles, and sensory evaluation. The optimal roasting conditions (150 ℃, 30 min, 0.26 ×g) promoted the formation of favorable volatile compounds. Roasting significantly increased oil extraction yield across all species ($p < 0.05$), with elevated AVs, PVs, and IVs compared to unroasted samples. Nevertheless, the peroxide values (PVs) remained below the Codex Alimentarius limit of 15 meq/kg, indicating that the samples can still be classified as edible vegetable oils with acceptable oxidative stability. IV and Fatty acid analysis revealed that *T. molitor* oils resembled canola, rapeseed and sesame oils. *L. migratoria* oil were abundant in linoleic acid and α-linolenic acid, which are essential fatty acids. Especially, these exhibited the highest PUFA/SFA ratio and lowest AI and TI among all species. Experimental conditions for volatile analysis using HS-SPME-Arrow-GC/MS afforded a wide linear range, high sensitivity, precision, and accuracy. Volatile analysis showed that roasted oils contained more diverse and concentrated volatile compounds than unroasted oils. Particularly, roasted insect oils were detected MRPs such as 2-pentylfuran, 2,5-dimethylpyrazine, 2,3-dimethylpyrazine, trimethylpyrazine, and methional. These compounds impart floral, caramel, and cocoa notes, enhancing the sensory complexity of roasted oils. Sensory evaluations confirmed that roasting increased odor-liking scores for all species by generating positive attributes (nutty, roasted, grainy, bread-like, and baked odors), while suppressing disliking factors (sour, spoiled, fishy, and ammonia odors). Although negative consumer perceptions of insect derived foods remain a challenge, these results suggest that roasting substantially improves both the sensory appeal and acceptability of edible insect oils.

This study represents the first comparative investigation of volatile and sensory characteristics in roasted and unroasted edible insect oils. The results suggest the potential of roasted edible insect oils as a functional ingredient in food applications

and as value added products in sustainable food systems. Future investigations should include pilot-to-industrial scale process validation, oxidative stability and shelf-life modelling, and integration with complementary unit operations such as supercritical CO_2 fractionation or targeted enzymolysis to consolidate and extend the sensory and nutritional enhancements delineated herein.

REFERENCE

Adelina, N. M., Wang, H., Zhang, L., & Zhao, Y. (2021). Comparative analysis of volatile profiles in two grafted pine nuts by headspace-SPME/GC-MS and electronic nose as responses to different roasting conditions. *Food Research International*, *140*, 110026. https://doi.org/10.1016/j.foodres.2020.110026

Alimentarius, C. (2015). *Codex alimentarius commission: Procedural manual.* , Rome: Joint

FAO/WHO Food Standards Programme. .

Alimentarius, C. (2023). Codex standard for named vegetable oils. *Codex stan*, *210*, 1-19.

Alonso-Esteban, J. I., González-Fernández, M. J., Fabrikov, D., de Cortes Sánchez-Mata, M., Torija-Isasa, E., & Guil-Guerrero, J. L. (2023). Fatty acids and minor functional compounds of hemp (Cannabis sativa L.) seeds and other Cannabaceae species. *Journal of Food Composition and Analysis*, *115*, 104962. https://doi.org/10.1016/j.jfca.2022.104962

AOAC. Official methods of analysis (18th ed). Washington, DC: Association of Official Analytical Chemists, (2005).

Bottle, E., Heredia-Olea, E., de la Rosa-Millan, J., Espinosa-Ramirez, J., & Tejada-Ortigoza, V. (2025). Molecular interactions tailoring the physicochemical, technofunctional, and texture characteristics of textured vegetable-insect proteins. *Food Chemistry*, *483*, 144287. https://doi.org/10.1016/j.foodchem.2025.144287

Cha, C. Y., & Lee, K. G. (2020). Effect of roasting conditions on the formation and kinetics of furan in various nuts. *Food Chemistry*, *331*, 127338. https://doi.org/10.1016/j.foodchem.2020.127338

Cha, J. Y., Han, J., Heo, J., Yu, H. H., Kim, Y. J., Jang, H. W., Kim, M. R., & Choi, Y. S. (2024). Variation of volatile compounds and sensory profile for *Protaetia brevitarsis* larvae fermented with lactic acid bacteria and yeast. *Food Chemistry*, *452*, 139480. https://doi.org/10.1016/j.foodchem.2024.139480

Chen, J. N., Zhang, Y. Y., Huang, X. H., Dong, M., Dong, X. P., Zhou, D. Y., Zhu, B. W., & Qin, L. (2023). Integrated volatolomics and metabolomics analysis reveals

the characteristic flavor formation in Chouguiyu, a traditional fermented mandarin fish of China. *Food Chemistry*, *418*, 135874. https://doi.org/10.1016/j.foodchem.2023.135874

Chen, Y., Tao, X., Hu, S., He, R., Ju, X., Wang, Z., & Aluko, R. E. (2024). Effects of phytase/ethanol treatment on aroma characteristics of rapeseed protein isolates. *Food Chemistry*, *431*, 137119. https://doi.org/10.1016/j.foodchem.2023.137119

Cheragheshahi, J., Mohamadi Sani, A., Mahdian, E., Mohseni, S., & Nazari, Z. (2025). Optimization of dark chocolate formulation with roasted coriander cake as cocoa substitute. *Food Chemistry: X*, *25*, 102166. https://doi.org/10.1016/j.fochx.2025.102166

Cheseto, X., Baleba, S. B., Tanga, C. M., Kelemu, S., & Torto, B. (2020). Chemistry and sensory characterization of a bakery product prepared with oils from African edible insects. *Foods*, *9*(6), 800. https://doi.org/10.3390/foods9060800

da Silva, J., Lucas, A., Menegon de Oliveira, L., da Rocha, M., & Prentice, C. (2020). Edible insects: An alternative of nutritional, functional and bioactive compounds. *Food Chemistry*, *311*, 126022. https://doi.org/10.1016/j.foodchem.2019.126022

De Jesus-Hernandez, A. C., Delgado-Macuil, R. J., Ruiz-Espinosa, H., & Amador-Espejo, G. G. (2023). High-power ultrasound bleaching technique for canola oil (*Brassica napus L.*): Pigments removal and quality parameters. *Food Research International*, *173*(Pt 2), 113449. https://doi.org/10.1016/j.foodres.2023.113449

Franca, A. S., Mendonça, J. C. F., & Oliveira, S. D. (2005). Composition of green and roasted coffees of different cup qualities. *LWT - Food Science and Technology*, *38*(7), 709-715. https://doi.org/10.1016/j.lwt.2004.08.014

Gao, P., Sun, B., Chen, Z., Yuan, Q., Zhong, W., Yin, J., Hu, C., He, D., & Wang, X. (2024). Effects of different amino acid enzymatic preparations on the quality and flavor of fragrant rapeseed oil. *Food Chemistry: X*, *21*, 101219. https://doi.org/10.1016/j.fochx.2024.101219

Giri, A., Osako, K., & Ohshima, T. (2010). Identification and characterisation of

headspace volatiles of fish miso, a Japanese fish meat based fermented paste, with special emphasis on effect of fish species and meat washing. *Food Chemistry*, *120*(2), 621-631. https://doi.org/10.1016/j.foodchem.2009.10.036

Gong, J., Zuo, Q., Wu, Z., Zhao, C., Wei, J., & Huang, Y. (2024). Unraveling the core microorganisms and metabolic pathways related to off-flavor compounds formation during Jiang-flavor *Baijiu* fermentation. *Food Chemistry: X*, *23*, 101660. https://doi.org/10.1016/j.fochx.2024.101660

Han, L., Li, G., Wang, X., Yu, B., Zhang, T., & Cheng, Y. (2024). Characterization of volatile compounds from healthy and citrus black spot-infected Valencia orange juice and essential oil by using gas chromatography-mass spectrometry. *Food Chemistry: X*, *22*, 101374. https://doi.org/10.1016/j.fochx.2024.101374

Hoon Lee, J., Kim, Y. J., Kim, T. K., Song, K. M., & Choi, Y. S. (2024). Effect of ethanol treatment on the structural, techno-functional, and antioxidant properties of edible insect protein obtained from Tenebrio molitor larvae. *Food Chemistry*, *437*(Pt 1), 137852. https://doi.org/10.1016/j.foodchem.2023.137852

Hromis, N., Lazic, V., Popovic, S., Suput, D., Bulut, S., Kravic, S., & Romanic, R. (2022). The possible application of edible pumpkin oil cake film as pouches for flaxseed oil protection. *Food Chemistry*, *371*, 131197. https://doi.org/10.1016/j.foodchem.2021.131197

Hu, B. B., Yin, W. T., Zhang, H. B., Zhai, Z. Q., Liu, H. M., & Wang, X. D. (2024). The interaction between lipid oxidation and the Maillard reaction model of lysine-glucose on aroma formation in fragrant sesame oil. *Food Research International*, *186*, 114397. https://doi.org/10.1016/j.foodres.2024.114397

Jung, M. Y., Baek, S. H., Lim, S. M., Chung, I. M., Han, J. G., & Kim, S. H. (2021). An unattended HS-SPME-GC－MS/MS combined with a novel sample preparation strategy for the reliable quantitation of C8 volatiles in mushrooms: A sample preparation strategy to fully control the volatile emission. *Food Chemistry, 347*, 128998. https://doi.org/10.1016/j.foodchem.2021.128998

Kim, T.-E., Yoo, G., Lee, M. H., Kim, B.-K., & Jang, H. W. (2022). Novel QuEChERS-ultra-performance liquid chromatography－atmospheric-pressure chemical ionization tandem mass spectrometry method for the simultaneous

determination of vitamin D and vitamin K in vitamin-fortified nanoemulsions. *Food Chemistry*, *389*, 133009. https://doi.org/10.1016/j.foodchem.2022.133009

Krumreich, F. D., Mendonça, C. R. B., Borges, C. D., Crizel-Cardozo, M. M., dos Santos, M. A. Z., Otero, D. M., & Zambiazi, R. C. (2024). Margarida avocado oil: Effect of processing on quality, bioactive compounds and fatty acid profile. *Food Chemistry Advances*, *4,* 100617. https://doi.org/10.1016/j.focha.2024.100617

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR: an R package for multivariate analysis. *Journal of statistical software*, *25*(1), 1-18. https://doi.org/10.18637/jss.v025.i01

Lee, G., Lee, M., Ahn, J., Kim, Y., & Lee, K.-G. (2023). Correlation analysis between volatile compounds and α-dicarbonyl compounds in various beans in response to different roasting conditions. *LWT*, *177,* 114544. https://doi.org/10.1016/j.lwt.2023.114544

Lee, G. E., Kim, Y. J., Jang, H. B., Cha, J. Y., Choi, Y. S., & Jang, H. W. (2023). Comparison of oil quality characteristics of *Locusta migratoria*, *Allomyrina dichotoma*, and *Tenebrio molitor* obtained using different extraction methods. *Journal of Insects as Food and Feed*, *9*(12), 1631-1642. https://doi.org/10.1163/23524588-20230039

Lee, J. H., Kim, Y. J., Kim, T. K., Song, K. M., & Choi, Y. S. (2024). Effect of ethanol treatment on the structural, techno-functional, and antioxidant properties of edible insect protein obtained from *Tenebrio molitor* larvae. *Food Chemistry*, *437*(Pt 1), 137852. https://doi.org/10.1016/j.foodchem.2023.137852

Lee, J. Y., Kim, W. S., Lee, Y. Y., Choi, Y. S., Choi, H., & Jang, H. W. (2019). Solid-phase microextraction Arrow for the volatile organic compounds in soy sauce. *Journal of Separation Science*, *42*(18), 2942-2948. https://doi.org/10.1002/jssc.201900388

Lee, M. H., Kim, T. K., Cha, J. Y., Yong, H. I., Kang, M.-C., Jang, H. W., & Choi, Y. S. (2022). Physicochemical characteristics and aroma patterns of oils prepared from edible insects. *LWT*, *16,* 113888 *7*. https://doi.org/10.1016/j.lwt.2022.113888

Lee, S., Choi, E., & Lee, K.-G. (2024). Kinetic modelling of Maillard reaction products and protein content during roasting of coffee beans. *LWT*, *211,* 116950.

https://doi.org/10.1016/j.lwt.2024.116950

Leonard, W., Zhang, P., Ying, D., & Fang, Z. (2023). Surmounting the off-flavor challenge in plant-based foods. *Critical Reviews in Food Science and Nutrition*, *63*(30), 10585-10606. https://doi.org/10.1080/10408398.2022.2078275

Li, N., Li, G., Guan, X., Li, A., & Tao, Y. (2025). Volatile aroma compound-based decoding and prediction of sweet berry aromas in dry red wine. *Food Chemistry*, *463*(Pt 2), 141248. https://doi.org/10.1016/j.foodchem.2024.141248

Ma, Y., Zhang, K., Xu, C., Lai, C., Liu, Y., Cao, Y., & Zhao, L. (2024). Contribution of lipid to the formation of characteristic volatile flavor of peanut oil. *Food Chemistry*, *442*, 138496. https://doi.org/10.1016/j.foodchem.2024.138496

Mansouri, F., Allay, A., Moumen, A. B., Benkirane, C., Taaifi, Y., Belhaj, K., Addi, M., Hano, C., Fauconnier, M.-L., Caid, H. S., Elamrani, A., & Zeb, A. (2023). Laboratory-Scale Optimization of Hemp Seed Roasting Temperature and Time for Producing a High-Quality Pressed Oil. *Journal of Food Processing and Preservation*, *2023*(1), 8261279. https://doi.org/10.1155/2023/8261279

Ministry of Food and Drug Safety. (2021). General test methods (in Korean). *Retrieved from https://various.foodsafetykorea.go.kr/fsd/#/ext/Document/FC*.

Nam, J. K., Kwak, B. M., & Jang, H. W. (2025). Optimization and comparative analysis of quality characteristics and volatile profiles in edible insect oils extracted using supercritical fluid extraction and ultrasound-assisted extraction methods. *Food Chemistry*, *474*, 143237. https://doi.org/10.1016/j.foodchem.2025.143237

Neugebauer, A., Granvogl, M., & Schieberle, P. (2020). Characterization of the Key Odorants in High-Quality Extra Virgin Olive Oils and Certified Off-Flavor Oils to Elucidate Aroma Compounds Causing a Rancid Off-Flavor. *Journal of Agricultrual and Food Chemistry*, *68*(21), 5927-5937. https://doi.org/10.1021/acs.jafc.0c01674

Otero, P., Gutierrez-Docio, A., Navarro Del Hierro, J., Reglero, G., & Martin, D. (2020). Extracts from the edible insects *Acheta domesticus* and *Tenebrio molitor* with improved fatty acid profile due to ultrasound assisted or pressurized liquid extraction. *Food Chemistry*, *314*, 126200. https://doi.org/10.1016/j.foodchem.2020.126200

Perez-Santaescolastica, C., De Winne, A., Devaere, J., & Fraeye, I. (2023).

Comparing the aromatic profile of seven unheated edible insect species. *Food Research International*, *164*, 112389. https://doi.org/10.1016/j.foodres.2022.112389

Ribeiro, J. C., Pintado, M. E., & Cunha, L. M. (2024). Consumption of edible insects and insect-based foods: A systematic review of sensory properties and evoked emotional response. *Comprehensive Reviews in Food Science and Food Safety*, *23*(1), e13247. https://doi.org/10.1111/1541-4337.13247

Shinohara, T., Kubodera, S., & Yanagida, F. (2000). Distribution of phenolic yeasts and production of phenolic off-flavors in wine fermentation. *Journal of Bioscience and Bioengineering*, *90*(1), 90-97. https://doi.org/10.1016/s1389-1723(00)80040-7

Sun, X., Zhang, B., Han, J., Wei, C., & Liu, W. (2022). Effect of roasting temperature and time on volatile compounds, total tocopherols, and fatty acids of flaxseed oil. *Journal of Food Science*, *87*(4), 1624-1638. https://doi.org/10.1111/1750-3841.16073

Suri, K., Singh, B., Kaur, A., Yadav, M. P., & Singh, N. (2020). Influence of microwave roasting on chemical composition, oxidative stability and fatty acid composition of flaxseed (*Linum usitatissimum L.*) oil. *Food Chemistry*, *326*, 126974. https://doi.org/10.1016/j.foodchem.2020.126974

Symoneaux, R., Galmarini, M., & Mehinagic, E. (2012). Comment analysis of consumer's likes and dislikes as an alternative tool to preference mapping. A case study on apples. *Food Quality and Preference*, *24*(1), 59-66. https://doi.org/10.1016/j.foodqual.2011.08.013

Tome-Rodriguez, S., Barba-Palomeque, F., Ledesma-Escobar, C. A., Miho, H., Diez, C. M., & Priego-Capote, F. (2023). Influence of genetic and interannual factors on the fatty acids profile of virgin olive oil. *Food Chemistry*, *422*, 136175. https://doi.org/10.1016/j.foodchem.2023.136175

Williams, E. J. (1949). Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Chemistry*, *2*(2), 149-168. https://doi.org/10.1071/CH9490149

Wood, J. D., Richardson, R. I., Nute, G. R., Fisher, A. V., Campo, M. M., Kasapidou, E., Sheard, P. R., & Enser, M. (2004). Effects of fatty acids on meat quality: a review. *Meat Science*, *66*(1), 21-32.

https://doi.org/10.1016/s0959-8049(03)00620-8

Yin, W. T., Ma, X. T., Li, S. J., Wang, X. D., Liu, H. M., & Shi, R. (2021). Comparison of key aroma-active compounds between roasted and cold-pressed sesame oils. *Food Research International*, *150*(Pt A), 110794. https://doi.org/10.1016/j.foodres.2021.110794

Yu, H., Zhang, R., Yang, F., Xie, Y., Guo, Y., Yao, W., & Zhou, W. (2021). Control strategies of pyrazines generation from Maillard reaction. *Trends in Food Science & Technology*, *112*, 795-807. https://doi.org/10.1016/j.tifs.2021.04.028

Zhang, L., Chen, J., Zhao, X., Chen, W., Du, S., & Yu, X. (2022). Key volatile compound formation of rapeseed oil induced via the Maillard reaction during seed roasting. *Food Chemistry*, *388*, 132992. https://doi.org/10.1016/j.foodchem.2022.132992

Zhang, W., Jia, Y., Guo, C., Devahastin, S., Hu, X., & Yi, J. (2024). Effect of compositions and physical properties on 3D printability of gels from selected commercial edible insects: Role of protein and chitin. *Food Chemistry*, *433*, 137349. https://doi.org/10.1016/j.foodchem.2023.137349

Zheng, L., Wang, S., Yang, Y., Zheng, X., Xiao, D., Ai, B., & Sheng, Z. (2024). Volatile aroma compounds of passion fruit seed Oils: HS-GC-IMS analysis and interpretation. *Food Chemistry: X*, *21*, 101212. https://doi.org/10.1016/j.fochx.2024.101212

Zhou, Y., Gao, S., Wei, J., Chen, X., Zhu, S., & Zhou, X. (2023). Systematical construction of rice flavor types based on HS-SPME-GC-MS and sensory evaluation. *Food Chemistry*, *413*, 135604. https://doi.org/10.1016/j.foodchem.2023.135604

Żołnierczyk, A. K., & Szumny, A. (2021). Sensory and chemical characteristic of two insect species: Tenebrio molitor and Zophobas morio larvae affected by roasting processes. *Molecules*, *26*(9), 2697. https://doi.org/10.3390/molecules26092697

ABSTRACT IN KOREAN (국문 요약)

본 연구는 로스팅이 다섯 가지 식용 곤충에서 추출한 지질의 휘발성 화합물과 관능적 특성에 미치는 영향을 조사합니다. 초음파를 이용한 추출을 통해 지질을 추출하였고, Box-Behnken 설계를 이용한 반응 표면 분석법을 이용하여 최적의 로스팅 조건(150℃, 30분, 0.26 ×g)을 확인했습니다. 휘발성 화합물은 headspace solid-phase microextraction arrow와 gas chromatography - mass spectrometry (HS-SPME-Arrow-GC/MS)를 병행하여 분석하였으며, 분석법 검증 결과 R^2 ≥ 0.9800, 회수율 90.09-109.98 %, 검출한계 1.03-62.52 ng/g, 정량한계 3.22-197.38 ng/g를 나타냈습니다. 로스팅은 2-pentylfuran과 pyrazines을 포함하여 소비자 기호도가 높은 마이야르 유래 휘발성 화합물의 생성을 증가시켰습니다. 관능 평가의 경우 로스팅 후 냄새 선호도가 증가하였는데, 이는 nutty, roasted, grainy, bread-like, and baked 향이 강화되고 sour, spoiled, fishy, and ammonia와 같은 향이 억제되었기 때문입니다. 이러한 결과는 로스팅 공정이 식용곤충 오일의 관능적 품질을 향상시키고 식품 개발에 활용될 수 있음을 시사합니다.