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Comparison of volatile compound profiles derived from various livestock protein alternatives including edible-insect, and plant-based proteins

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ABSTRACT

In this study, the distinctive chemical fingerprints that contribute to the flavor characteristics of various protein materials, such as insects, plant-based protein, and livestock, were investigated. In edible-insects (*Tenebrio molitor* and *Protaetia brevitarsis*), aldehydes and cyclic volatile compounds were the predominant volatile components and had distinct flavor characteristics such as cheesy, sharp, green, floral, and sweet. In contrast, the relatively high levels of pyrazines and furans in plant-based protein materials, such as textured vegetable and pea protein. They included unique flavor properties characterized by sweet, fatty, grassy, creamy, and roasted. The primary volatile chemical group detected in livestock protein materials, such as a pork and a beef, was ketones. The pork sample showed specific flavors, such as alcoholic, green, and fruity, while a beef presented distinctive flavor, including creamy, fruity, and alcoholic. Based on the results, this research provided the understanding of the flavor aspects of diverse protein materials.

1. Introduction

The global food landscape is rapidly evolving, driven by a growing awareness of the environmental, ethical, and health implications associated with traditional livestock production (Liu et al., 2023). Alternative non-animal protein materials have gained significant attention as potential solutions to these challenges (Kumar et al., 2023). The quest for alternative proteins arises from the pressing need to feed a burgeoning global population while mitigating the adverse effects of traditional meat production (Kim et al., 2019; Köhler et al., 2019). Livestock farming contributes significantly to greenhouse gas emissions, land use, and water consumption (Kim, Cha, et al., 2022). In contrast, alternative proteins have shown promise in terms of the potential to reduce the environmental footprint associated with food production (Kim, Kim, et al., 2022). Among then, edible insects and plant-based proteins are two such alternatives with unique flavor attributes and culinary potential (Kim et al., 2023).

Edible insects, often referred to as entomophagy, have been a part of the human diet for centuries in various cultures around the world (Yong et al., 2023). Approximately 2000 species of insects have been considered edible, with the majority (>49%) being beetles and caterpillars (Ordoñez-Araque & Egas-Montenegro, 2021). They are prized for their high protein content, sustainability, and low environmental impact (Lee, Kim, et al., 2023). Insects can be reared with minimal resources and produce less greenhouse gas emissions compared to traditional livestock (van Huis et al., 2013). As they grow in popularity, understanding the volatile compound profiles of edible insects is vital to improve their acceptance and utilization in the food industry (Jeon et al., 2024). Despite the nutritional values and benefits as a food processing additive, edible insects have met with reluctance by consumers in many countries. To reduce consumer aversion, it involves using edible insect flour in food or incorporating isolated edible insect components into food to make the insects invisible (Zielińska et al., 2018).

Plant-based proteins have gained prominence as a viable substitute for meat owing to their versatility and ability to mimic the taste and texture of traditional meats (Lee, Lee, et al., 2023). These proteins are derived from materials, such as soy, peas, and fungi, and are becoming increasingly popular among consumers seeking sustainable alternatives (Lee, Jo, et al., 2023). Analyzing the volatile compounds in plant-based proteins can help elucidate the complex flavors and aromas that play a

Abbreviations: TM, *Tenebrio molitor*; PB, *Protaetia brevitarsis*; TVP, textured vegetable protein; TPP, textured pea protein; SPME, solid-phase microextraction; GC–MS, gas chromatography–mass spectrometry; ANOVA, analysis of variance; PCA, Principal component analysis; OPLS-DA, orthogonal partial least-squares discriminant analysis; Acetoin, 3-hydroxybutan-2-one; VIP, variable importance in the projection; pcorr, the correlation coefficient value of variable importance.

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crucial role in their acceptance among consumers. In particular, protein materials transformed from powdered forms using plant-based protein and water into structured materials are widely used in the food industry for the development of alternative foods. However, researches have been conducted on volatile compounds and their precursors derived from plant-based materials to address issues, such as off-flavors inherent in the material itself, which can compromise the quality of meat alternatives (Sakai et al., 2023;.Xu et al., 2024).

In this study, we aimed to investigate volatile compounds that contribute to the flavor attributes of edible insects, plant-based proteins, pork, and beef. Several alternative protein materials highly suitable for industrial applications, such as *Tenebrio molitor* (mealworm), *Protaetia brevitarsis seulensis* (kolbe), textured vegetable protein and textured pea protein, were selected (Baune et al., 2022; Gkinali et al., 2022; Sim et al., 2018). There have been various studies on the flavor of alternative proteins. This study, however, has taken a different approach from previous researches. Previous studies have focused on the qualitative and quantitative results of individual volatile compounds from each protein material (Ebert et al., 2022; Kröncke et al., 2019). Moreover, most studies have centered on the potential applicability of alternative proteins across various food products (Chekmarev et al., 2022; Gkarane et al., 2020; He et al., 2021; Nissen et al., 2020), while research into the distinct flavor attributes of the raw materials has been limited. This study emphasized on comprehensive insights into the volatile compound profile, like a flavor fingerprint.

2. Material and methods

2.1. Chemicals and reagents

Methanol and 2-methyl-4-heptanone were purchased from Sigma-Aldrich (USA).

2.2. Sample preparation

Three different types of protein materials, including livestock, plant-based protein materials, and insects were considered to compare the volatile compound profiles derived from each material and identify flavor characteristics specific to each protein material. Table 1 briefly provides some information on the sample. Livestock materials, including raw beef (sirloin) and pork (sirloin), were obtained from a local market in Korea. Ground freeze-dried powders of edible insects, such as *Tenebrio molitor* (TM) and *Protaetia brevitarsis seulensis* (PB), were purchased from a local market (Farmbang, Sunchang, Korea). Plant-based protein materials, such as textured vegetable protein (TVP) and textured pea protein (TPP), were obtained from Hokyoung Tech Co., Ltd. (Anseong, Korea). In this study, TVP and TPP, which are underwent the processing, were selected to investigate the volatile compound profiles of plant-based food materials that are primary used as alternatives for animal protein.

2.3. Volatile compound analysis

Solid-phase microextraction (SPME) was performed to extract volatile compounds. Before the extraction, the solid samples such as beef and pork, were grounded under liquid nitrogen conditions. The sample (3.0 g) was placed into an amber vial (20 mL) with an internal standard (2 μL, 2-methyl-4-heptanone, 100 ppm in methanol). It was equilibrated for 30 min at 40 °C, and the absorption was conducted for 30 min at 40 °C with a fiber coated divinylbenzene/ carboxen/polydimethylsiloxane/ fiber (DVB/CAR/PDMS, 50/30 μm, Supelco, Bellefonte, PA, USA).

The samples were analyzed via gas chromatography–mass spectrometry (GC–MS) using a 7890 A Agilent GC system (Agilent Technologies, Santa Clara, CA, USA) coupled with 5975C MSD mass detector (Agilent Technologies). A DB-WAXUI capillary column (30 m × 0.25 mm i.d. × 0.25 μm film thickness, J&W Scientific, Folsom, CA, USA) was used for the separation of volatile compounds. Helium (99.999%) was used as the carrier gas at a flow rate of 0.8 mL/min. The temperatures of injector and transfer were 230 °C and 250 °C, respectively. The oven was started at a temperature of 40 °C for 5 min, which was increased to 200 °C at a rate of 4 °C per min and maintained for 2 min. The volatile compounds were obtained via electron impact (EI) ionization at 70 eV and scanned in the range of 35–350 amu (a.m.u.). The identification of volatile compounds was confirmed by comparing retention times and mass spectral data with those of authentic standard compounds or data in a commercial GC–MS library (Wiley7.0 and W9N08). The retention indices (RI) of the volatile compounds were calculated with n-alkanes (C_7 to C_{22}). The content of each volatile compound was calculated by comparing their peak areas with that of an internal standard. All experiments were conducted at least three times.

2.4. Statistical analysis

Volatile compound results were expressed as the mean ($n = 3$) ± standard deviation (SD) in Table S1. An analysis of variance (ANOVA) was conducted using Duncan's multiple range test to compare the significant differences ($p < 0.05$) between samples using SPSS (version 20.0, Chicago, IL, USA). Principal component analysis (PCA) and orthogonal partial least-squares discriminant analysis (OPLS-DA) were conducted to determine flavor characteristics among the samples using SIMCA 16 (Umetrics, Umea, Sweden).

3. Results and discussions

A total of 167 volatile compounds were identified in all the samples. Table S1 lists the identified volatile compounds and their RIs and relative peak areas. The samples varied in the number of volatile compounds detected as follows: TM, 75 volatile compounds, PB, 79 volatile compounds, TVP, 77 volatile compounds, TPP, 60 volatile compounds, pork, 33 volatile compounds, beef, 49 volatile compounds. Some authors have considered the relationship between the chemical groups of volatile compounds and their retention rates from the matrix, considering their different polarity and affinity toward the matrix (Le Thanh et al., 1992; Rosenberg et al., 1990). Therefore, the identified volatile compounds were classified by the chemical functional groups. Aliphatic hydrocarbons were classified as acids, aldehydes, alcohols, esters, ketones, and hydrocarbons. Cyclic hydrocarbons included terpenes and benzenes & benzene derivatives. Nitrogen-containing compounds were categorized as N-containing compounds, pyrazines, and pyrroles, whereas oxygen-containing compounds were classified as O-containing compounds, furans, and furanones. Also, sulfur-containing compounds and miscellaneous compounds were classified as distinct groups.

Table 1
Sample information.*

Items	Beef	Pork	TVP	TPP	TM	PB
Category	Livestock	Livestock	Plant-based	Plant-based	Insect	Insect
Origin	Cow (Sirloin)	Pig (Sirloin)	Soybeans Wheat	Peas	*Tenebrio molitor*	*Protaetia brevitarsis seulensis*
Processing	Raw	Raw	Extruded	Extruded	Lyophilization	Lyophilization

* TM, *Tenebrio molitor*; PB, *Protaetia brevitarsis seulensis*; TVP, Textured vegetable protein; TPP, Textured pea protein.

3.1. Comparison of volatile compound profiles among different protein materials

Fig. 1 shows the relative quantitative ratios of identified volatile compounds organized by chemical group for each material and the major volatile compounds within each chemical group. Based on these results, insect protein materials showed distinct volatile compound profiles depending on the type of insect, compared to other materials. TM was predominantly composed of aldehydes (47.7%), benzenes and benzene derivatives (17.0%), acids (13.1%), and terpenes (10.2%), whereas PB mainly characterized by benzenes and benzene derivatives (37.4%), terpenes (36.5%), alcohols (7.6%), and esters (4.7%). In the insect protein materials, cyclic hydrocarbons such as terpenes, benzene, and benzene derivatives, equally constituted a higher proportion compared to other protein materials such as plant-based and livestock materials. Among the cyclic hydrocarbons, limonene and xylene accounted for the majority. Limonene, which is often detected in citrus fruits, has a fresh citrus odor (Rodríguez et al., 2017). Xylenes such as 1,3-xylene, 1,4-xylene, and ethylbenzene showed a high quantitative ratio in the benzene group. Xylenes have been reported to exhibit artificial aroma characteristics like those of plastics, and their precursor is known to be 2,5-dimethylfuran, which is mainly derived from the decomposition of carbohydrates (Dutta & Bhat, 2023).

We found that short & medium chain-length fatty acids (up to C_4) and their derivatives such as hexanoic acid, pentanoic acid, hexanal, and pentanal comprised the main components of TM. Several previous studies have reported that aldehydes are important volatile compounds that contribute to the characteristic flavor of TM (Keil et al., 2022; Seo et al., 2020). In particular, hexanal, which is a major byproduct of the oxidation reaction of n-6 polyunsaturated fatty acids, constituted a high proportion (34.0%) of the volatile compounds in TM. Hexanal has unique aroma characteristics with a strong fatty green aroma at a low threshold (4.5 ppb) (do Batista et al., 2015). In contrast, PB showed a relatively high proportion of limonene (29.0%) compared to the other protein materials. Some studies on the volatile compound profile of PB have been performed regarding the fatty acid composition and volatile compounds of the powder (Yeo et al., 2013), as well as protein extracts from PB (Lee et al., 2021). They reported that hydrocarbons were the main volatile compounds in PB. However, in this study, cyclic hydrocarbons predominated. This might have been caused by differences in volatile extraction methods or preprocessing of samples.

The plant-based protein materials, including TVP and TPP, simulated the texture of meat products using soybean or pea protein using heat and pressure through extrusion processing. In this study, they were distinguished by having undergone more processing compared to other protein materials. The TVP was primarily composed of soybeans and wheat, aldehydes (25.0%), alcohols (23.3%), and benzene & benzene derivatives (16.2%), being predominant. In contrast, TPP, which is made of pea proteins, was characterized by acids (30.0%), ketones (16.9%), pyrazines and pyrroles (13.6%), and furans and furanones (9.5%) as the main components. The detection of pyrazines and furans in plant-based protein materials was a distinctive characteristic that set them apart from other protein materials. Pyrazines, which mainly have a roasted, nutty odor, are heterocyclic nitrogen compounds formed through non-enzymatic Maillard reaction (Yu et al., 2021). Among furans, 2-pentylfuran, which constituted a high quantitative ratio in the furan category, is known to have linoleic acid as its precursor, and is recognized as a compound with a strong beany aroma, exhibiting a very low threshold and having a negative impact (Kato et al., 1981). It is known to be an essential component of the stable beany odor in heated conditions, with an increase in its generation under exposure to light and high temperatures (Kanavouras et al., 2004). The acceptability of many plant proteins may be limited by off-flavor characteristics, such as beany, musty, and earthy odor derived from fatty aldehydes and alcohols (Bott & Chambers IV, 2006).

In the results for TVP, aldehydes constituted the highest proportion (25.0%), and hexanal, pentanal, and other aldehydes derived from medium-chain fatty acids being detected prominently. In alcohols (23.3%), ethanol, oct-1-en-3-ol, and 1-methoxypropan-2-ol were detected prominently. Ethanol is a volatile aromatic compound with an alcoholic fragrance that is formed naturally through enzymatic reactions and other processes. Oct-1-en-3-ol, which has a strong mushroom-like and musty odor, is generated through the enzymatic breakdown and oxidation of linoleic acid (Wurzenberger & Grosch, 1984). Hydrocarbons were also present at higher levels compared to other protein materials, but their threshold values are high, and they mainly do not have distinctive aromatic characteristics. Therefore, they generally do not have a significant impact on the aroma of a material.

In TPP, acids constituted a relatively high quantitative ratio (30.0%), with acetic acid accounting for the majority at 25.4%. Acetic acid, which has a pungent, vinegar-like aroma, has a high threshold of 22,000 ppb. However, it showed a high quantitative value, suggesting that it may have an impact with sour and fermented odor descriptions. Ketones were also present in high proportions, with propan-2-one (acetone) and 1-hydroxy-propan-2-one (hydroxyacetone) constituting the majority. In contrast, furan-2-ylmethanol and 2-pentylfuran were present in high proportions. Among them, furan-2-ylmethanol exhibits burned, cooked aroma characteristics and is primarily generated through non-enzymatic reactions induced by heating, such as the Maillard reaction. Ebert et al. (2022) reported that hexanal, nonanal, 2-undecanone, (E)-2-octenal, (E, Z)-3,5-octadiene-2-one, (E,E)-2,4-decadienal, 2-pentylfuran, 2-pentylpyridine, and γ-nonalactone were major contributors to the flavor of pea protein. Acetic acid, however, was not found as a significant volatile compound in the pea protein product. These differences in the volatile compound profiles might be explained by differences in the raw materials and variations in processing such as excluding processing.

In the case of animal-derived proteins such as pork and beef, ketones were primarily detected among the total volatile compounds, constituting approximately 65%–70% of the overall composition. In pork, the primary detected compounds were ketones, aldehydes, and alcohols, while in beef, ketones, alcohols, acids, and esters were predominantly found. The majority of ketones in both cases were represented by 3-hydroxybutan-2-one (acetoin), which imparts a creamy-buttery and yogurt-like aroma characteristic. Acetoin is known to be produced through the decarboxylation of α-acetolactate or the reduction of diacetyl (Audrain et al., 2015). Pork was characterized by a high quantitative ratio of aldehydes and alcohols, with elevated levels of 3-methylbutanal (8.6%) and 3-methylbutan-1-ol (16.4%). Both 3-methylbutanal and 3-methylbutan-1-ol compounds are generated through leucine degradation in the presence of α-dicarbonyl compounds (Pripis-Nicolau et al., 2000). 3-methylbutanal is recognized for its low threshold (0.2–2 ppb) and malty, almond-like aroma characteristics, whereas 3-methylbutan-1-ol is known for its whiskey-like aroma traits. In beef, acids, alcohols, and esters showed a higher quantitative ratio in descending order after ketones. According to the results, acetic acid (4.3%) was predominant among acid, whereas ethanol (5.8%) and pentan-1-ol (3.4%) were prominent among alcohols. Esters, known for their fruity, sweet, and fatty aroma characteristics, predominantly featured methyl acetate (3.8%) with a sweet aroma trait.

3.2. The identification of specific volatile compounds in protein-based materials

In this study, multivariate statistical analysis was employed to process a large amount of data, a data summarization technique that elucidates the individual characteristics of collected volatile compounds. Multivariate statistical analysis was utilized to identify common factors among all variables, determine the extent of influence of each variable, and elucidate the characteristics of the different groups. We also used principle component analysis (PCA), which is a widely applied unsupervised clustering method that reduces dimensions while largely preserving the variance of multivariate data without requiring prior

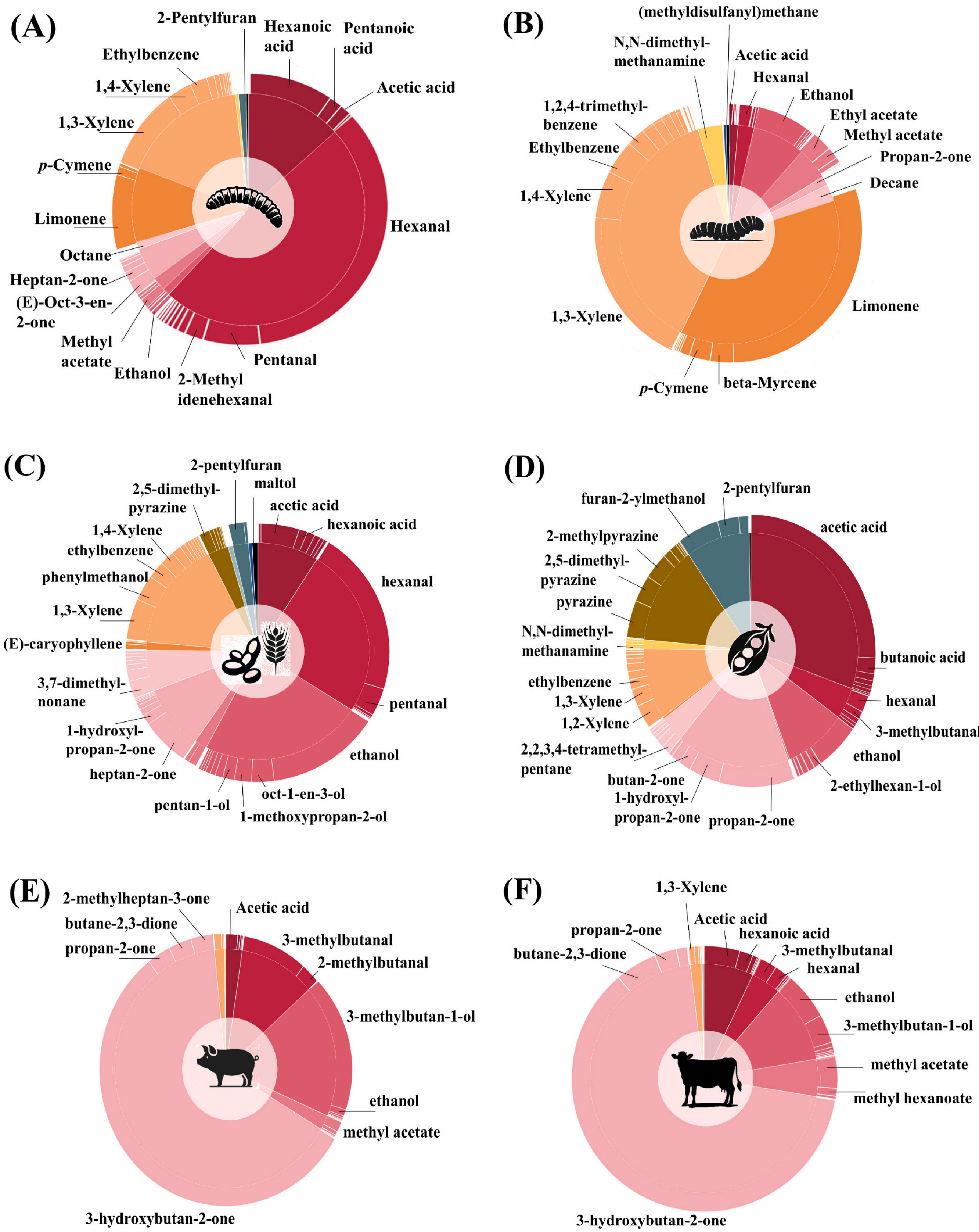

Fig. 1. Circle map based on the percentage quantitative ratio of identified volatile compounds derived from different protein materials: (A), TM, *Tenebrio molitor*; (B), PB, *Protaetia brevitarsis seulensis*; (C), TVP, Textured vegetable protein; (D), TPP, Textured pea protein; (E), Pork; (F), Beef.

knowledge of the dataset (Eriksson et al., 2005).

Fig. 2 presents the results of the principal component analysis (PCA) based on the quantitative analysis of the identified volatile aroma compounds collected by SPME-GC/MS. Figs. 2(A) and (B) respectively depict 2D and 3D score plots of the samples containing information on the overall volatile aroma compounds. The model explained 60% of the total variability of the variables, with R^2X at 0.997 and Q^2 at 0.998, which confirmed the appropriateness of the model without overfitting. The relative similarity or difference in the volatile compound profiles can be explained by the distance between the samples. In the score plot shown in Fig. 2(A), the distances between TVP, TPP, beef, and pork were relatively close, whereas insect protein was classified as relatively distant from the other samples. It could be attributed to the volatile compound profiles in insect proteins exhibiting a distinct different profile compared to other protein materials. Fig. 2(B) shows a 3D plot obtained by adding the principal components PC1, PC2, and PC3, which explain the variability of the variables. This accounted for 78% of the total variability of the variables. In Fig. 2(A), TVP, TPP, beef, and pork were shown to be relatively close to each other in the score plot. However, pork and beef were still located in similar positions as shown in Fig. 2(B), whereas TPP and TVP showed different directions from beef and pork. In addition, TVP and TPP demonstrated distinct directions from each other in the 3D score plot. Based on the results of the PCA, insect proteins were confirmed to possess a distinct volatile compound profile that distinguishes them from other protein materials. Among the samples used in this study, although the plant-based protein materials were produced using processing procedure unlike other proteins, the effects derived from raw materials contributed more to distinguishing volatile compound profiles than the effects of the processing.

An orthogonal partial least-squares discriminant analysis (OPLS-DA) was conducted to identify the specific volatile compounds in each protein. OPLS-DA is a multivariate analysis technique that rotates variable factors to maximize the separation between groups, thereby enhancing the distinction between observation groups (Triba et al., 2015). To derive protein material-specific volatile compounds, variable importance in the projection (VIP) values and the correlation coefficient value of variable importance (pcorr) were used as criteria in each OPLS-DA model (VIP > 1, $|\text{pcorr}| > 0.9$). The suitability of the OPLS-DA models was confirmed by conducting a permutation test 100 times. The results showed that the R^2 value representing the fitness of the model was lower than the original R^2, and the Q^2 intercept value, which is indicative of the predictive ability of the model, was negative, confirming the statistical significance of the model.

Using the OPLS-DA model, volatile components contributing to the differentiation of each protein material were selected. The flavor characteristics of each protein material were determined based on their proportions in the total volatile components and by considering each odor description. This study aimed to roughly predict flavors that can be expressed based on the type of protein used in the development of alternative foods that mimic original meat products. The flavor characteristics derived from the OPLS-DA results may be considered as distinctive flavor fingerprints that differentiate them from the dominant flavors of each protein material, rather than being the dominant flavor of each protein material compared to others. Sensory perception of flavor involves considering diverse factors, such as the threshold levels of compounds, affinity with the matrix, and relationships with other components (Guichard, 2002). However, we focused on predicting the approximate flavor characteristics specific to different materials based on quantitative values of compounds and aromatic descriptors that differentiate them from other materials in this work.

Table 2 presents the values of variable importance in the projection (VIP) and the correlation coefficient value of variable importance (pcorr) and odor descriptions for the selected volatile compounds. The odor descriptions of the selected compounds were classified into 14 categories based on commonly used words: sweet, fruity, caramelic, roasted, creamy, fatty, floral, sharp, green, grassy, earthy, woody, alcoholic, and cheesy, and are represented in the radial graphs shown in Fig. 3. The numbers located outside the circle represent the quantitative ratios of volatile compounds that fell within the corresponding odor category among the total volatile components.

Previous studies have demonstrated that the family and species of insects play a crucial role in determining the number, type, and quantity of volatile compounds related to the sensory properties of each type of edible insect (Meyer-Rochow et al., 2021; Perez-Santaescolastica et al., 2022) In this study, TM featured 30 selected volatile compounds that mainly expressed grassy, creamy, sharp, cheesy, and caramelic aroma characteristics. TM showed a high proportion (10.17%) of volatile compounds with a cheesy aroma, followed by quantified ratios of odor characteristics, such as sharp, green, and fruity. For PB, despite being the same insect protein, the compounds displayed different aromatic characteristics. Volatile compounds with a sharp peak showed the highest quantified ratio (4.95%), accompanied by floral, sweet, fruity, and other aroma characteristics.

Plant-based protein materials are known to contain not only fatty acid-derived aldehydes and alcohols that have green odor characteristics through heat-induced lipid oxidation (Zamora et al., 2015) but also pyrazines generated by the Maillard reaction, resulting in nutty and roasted flavors (Xu et al., 2019). The plant-based protein material TVP showed the highest quantified ratio of volatile compounds with sweet and fatty characteristics, along with greasy, alcoholic, roasted, and floral aroma characteristics. In contrast, for TPP, roasted aromas had the highest ratio, and creamy, green, sweet, sharp, earthy, and alcoholic

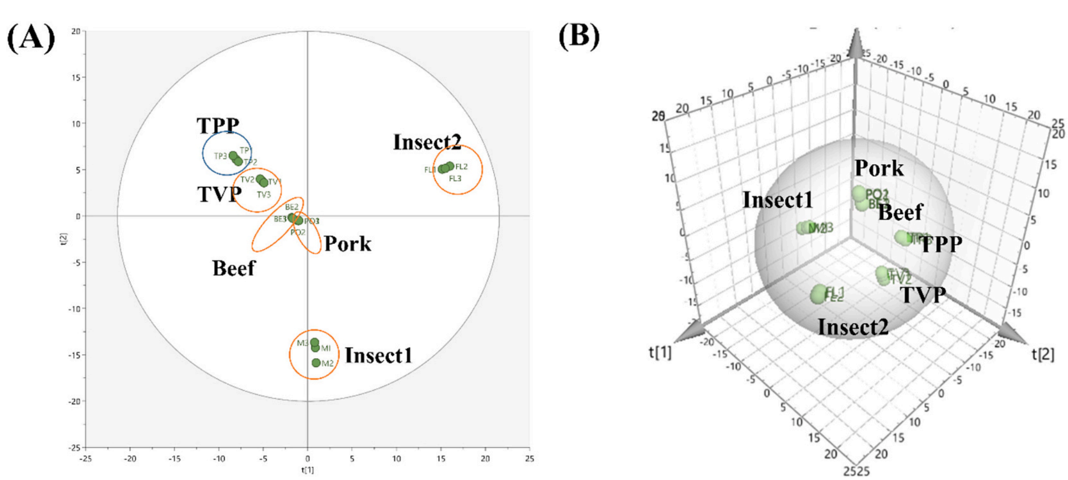

Fig. 2. PCA score plot based on the volatile compounds derived from various protein materials: (A), the 2D score plot; (B) the 3D score plot.

Table 2
Flavor characteristics derived from protein materials.

No.	Compound	VIP[b]	pcorr[c]	Odor description[a]	Category
TM-specific					
vo86	3-ethylcyclopentan-1-one	1.57	−0.96	caramellic	caramelic
vo5	octane	1.59	−0.97	gasoline-like	sharp
vo148	2-ethyl-2H-furan-5-one	1.60	−0.98	caramellic	caramelic
vo159	5-pentyloxolan-2-one	1.60	−0.98	Strong, fatty, coconut odor and taste	fatty
vo155	heptanoic acid	1.61	−0.98	Fatty, sour-sweat-like, rancid odor; cheesy	cheesy
vo152	hexanoic acid	1.62	−0.98	Heavy, fatty, cheesy-sweaty odor and taste	cheesy
vo108	(*E*)-oct-2-enal	1.62	−0.99	Fatty, green vegetable odor; fatty-green vegetable	grassy
vo83	oct-1-en-3-one	1.62	−0.99	Powerful, harsh metallic mushroom like odor	earthy
vo54	heptanal	1.62	−0.99	Fatty-rancid; in dilution sweet	cheesy
vo88	octane-2,5-dione	1.62	−0.99	fresh cream, fruity nutty	creamy
vo68	ethyl hexanoate	1.63	−0.99	Strong, fruity, pineapple, banana with strawberry	fruity
vo150	6-methyloxan-2-one	1.63	−0.99	Sweet, cream, buttery, chocolate notes	creamy
vo107	cyclohex-2-en-1-one	1.63	−1.00	gassy-minty odor	grassy
vo34	(E)-hex-2-enal	1.63	−1.00	Strong, leafy-green, fruity, pungent, apple, vegetable-like odor	green
vo110	(*Z*)-limonene oxide	1.63	−1.00	Sweet, citrus; very slight spearmint-herbaceous-fruity notes	fruity
vo8	oct-2-ene	1.63	−1.00	sweet odor	sweet
vo151	5-propyloxolan-2-one	1.64	−1.00	Coconut, hay-like	earthy
vo84	(Z)-hept-2-enal	1.64	−1.00	fatty, green. Fruity	grassy
vo141	(Z)-2-butyloct-2-enal	1.64	−1.00	green	green
vo47	2-methylidenehexanal	1.64	−1.00	pungent	sharp
vo80	octanal	1.64	−1.00	Fatty-fruity odor; sweet, citrus-orange-fatty taste	fruity
vo17	4-Nonene	1.64	−1.00	sharp, gasoline-like	sharp
vo9	butanal	1.64	−1.00	fruity, malt-like green odor & taste	fruity
vo4	propanal	1.64	−1.00	Breathtaking green acetaldehyde-like odor	green
vo146	d-Carvone	1.64	−1.00	Caraway odor & taste	sharp
vo144	(2E,4E)-nona-2,4-dienal	1.64	−1.00	Strong fatty type odor and taste; chicken fat on dilution	fatty
vo97	2-methylhept-2-enal	1.64	−1.00	powerful green grassy, slightly fruity	grassy
vo123	undecan-6-one	1.64	−1.00	fruity	fruity
vo143	5-ethyloxolan-2-one	1.64	−1.00	Coumarin-like, sweet odor and taste; creamy note	creamy
vo81	hexanenitrile	1.64	−1.00	pungent, fresh	sharp
PB-specific					
vo21	ethyl 2-methylpropanoate	1.51	−0.99	Sweet, ethereal, fruity rum like odor and taste; apple notes	fruity
vo165	ethyl hexadecanoate	1.51	−0.99	Faint, waxy, sweet odor; nearly tasteless; creamy mouthfeel	creamy
vo49	beta-myrcene	1.52	−0.99	Resinous terpene odor; balsamic-herbaceous-citrus taste	sharp
vo166	ethyl hexadec-9-enoate	1.52	−0.99	Fatty-oily odor, adds mouthfeel	fatty
vo3	methylsulfanylmethane	1.52	−0.99	Pungent, cabbage, cooked vegetable odor	grassy
PB -specific					
vo30	dec-1-ene	1.52	−0.99	Pleasant, floral	floral
vo39	beta-pinene	1.53	−1.00	Dry, woody, pne like, resinous odor; turpentine like taste	earthy
vo24	decane	1.53	−1.00	Hydrocarbon odor (gasoline-like)	sharp
vo161	ethyl tetradecanoate	1.53	−1.00	Mild sweet, waxy-fatty odor & sweet waxy creamy taste	creamy
vo119	alpha-copaene	1.53	−1.00	Woody, spicy	woody
vo160	3-phenylpropan-1-ol	1.53	−1.00	balsamic-floral, sweet, mild	floral
vo27	methyl 2-methylbutanoate	1.53	−1.00	Resinous, pine odor; turpentine taste	sharp
vo118	3-(prop-2-enyldisulfanyl)-prop-1-ene	1.53	−1.00	Strong, pungent, Garlic odor and taste	sharp
vo139	ethyl benzoate	1.53	−1.00	Floral, fruity-wintergreen ylang-ylang like odor	floral
vo41	sabinene	1.53	−1.00	Spicy terpenic citrusy	sharp
vo134	methyl benzoate	1.53	−1.00	Strong, sweet, fruity-floral ylang odor	fruity
vo136	2-(2-ethoxyethoxy)ethanol	1.53	−1.00	mild pleasant, sweet	sweet
vo103	2,5-dimethyl-3-propylpyrazine	1.53	−1.00	nutty odor	roasted
vo100	(methyltrisulfanyl)methane	1.53	−1.00	Strong, cabbage & cauliflower notes odor and taste	grassy
vo59	beta-phellandrene	1.53	−1.00	Fresh, spicy, citrus, peppery	sharp
vo109	1-methyl-2-prop-2-enylbenzene	1.53	−1.00	green, fresh peeled carrots	green
vo33	ethyl 2-methylbutanoate	1.53	−1.00	Strong, green, fruity, apple odor and taste	fruity
vo89	1,2,3-trimethylbenzene	1.53	−1.00	characteristic sweet odor	sweet
vo113	(−)-Menthone	1.53	−1.00	minty	sharp
vo132	propane-1,2-diol	1.53	−1.00	sweet flavor	sweet
vo138	1-phenylethanone	1.53	−1.00	Sweet, cherry-like odor and taste	fruity
vo77	alpha-terpinolene	1.53	−1.00	Sweet, piney, citrus, pleasant odor	fruity
TVP-specific					
vo69	gamma-terpinene	1.85	−0.99	Refreshing herbaceous-citrus like terpene odor & flavor	green
vo50	pent-1-en-3-ol	1.85	−0.99	Pungent, grassy, alliaceous-wasabi; green vegetable, tomato taste	grassy
vo125	3,7-dimethylocta-1,6-dien-3-ol	1.85	−0.99	Floral-woody, faint citrus note odor; sweet floral & slight citrus taste	floral
vo153	phenylmethanol	1.87	−0.99	Faint, sweet, almond fruity aroma; sweet	sweet
vo25	3,7-dimethylnonane	1.87	−1.00	mild, waxy	fatty
vo135	(E)-oct-2-en-1-ol	1.87	−1.00	green, vegetable-like.	green
vo99	hexan-1-ol	1.87	−1.00	Chemical, winey, slight fatty-fruity odor	grassy
vo91	2-ethylpyrazine	1.87	−1.00	Musty, nutty, buttery, peanut odor; chocolate-peanut, burnt praline taste	roasted

(*continued on next page*)

Table 2 (*continued*)

No.	Compound	VIP[b]	Pcorr[c]	Odor description[a]	Category
vo164	2-dodecoxyethanol	1.87	−1.00	bland odor	alcoholic
vo19	2-ethylfuran	1.87	−1.00	Strong, sweet-ethereal, burnt brown	sweet
vo35	2,2-dimethyloctane	1.87	−1.00	faint odor odorless	–
vo11	1,1-diethoxyethane	1.88	−1.00	Fruity, choking alcoholic, whiskey taste	alcoholic
TPP-specific					
vo74	2-methylpyrazine	1.74	−0.98	Green, nutty, cocoa, musty, potato, fishy-ammoniacal notes	roasted
vo117	2-oxopropyl acetate	1.75	−0.99	Fermented, sour fruity-buttery, caramellic notes	creamy
vo127	longifolene	1.75	−0.99	Weak sweet slightly camphoraceous woody note	green
vo101	2-ethyl-6-methylpyrazine	1.75	−1.00	Roasted, hazelnut, cocoa, cooked potato like notes	roasted
vo62	pyrazine	1.75	−1.00	Musty, raw nut like, corn-like, roasted hazelnuts	roasted
vo16	propan-2-ol	1.76	−1.00	Characteristic unpleasant “rubbing-alcohol” odor	alcoholic
vo140	furan-2-ylmethanol	1.76	−1.00	creamy, caramellic notes flavor	creamy
vo82	1-hydroxypropan-2-one	1.76	−1.00	Slightly green	green
vo106	Tetradecane	1.76	−1.00	gasoline-like	sharp
vo115	furan-2-carbaldehyde	1.76	−1.00	Sweet, cereal, bread-like	sweet
vo145	naphthalene	1.76	−1.00	Characteristic dry tarry camhorous hydrocarbon odor; musty taste	earthy
vo149	acetamide	1.76	−1.00	mousy odor	earthy
vo104	2,3,5-trimethylpyrazine	1.76	−1.00	Baked potato, roasted nut, cocoa, coffee, burnt odor & taste	roasted
Pork-specific					
vo48	2-methylheptan-3-one	2.09	−0.89	fruity. Fruity green leafy	fruity
vo72	pentan-1-ol	1.57	−0.93	Sweet, fresh, green, herbal, fruity	green
vo94	3-methylbut-2-en-1-ol	1.54	−0.94	Fruity, green, slight lavender odor and taste	floral
vo14	3-methylbutanal	2.23	−0.96	Pungent, cocoa, green fruity odor	green
vo28	methyl 3-methylbutanoate	1.84	−0.97	Strong, fruity, ethereal, pineapple-apple & juicy fruit odor and taste	fruity
vo13	2-methylbutanal	2.25	−0.98	Strong, cocoa-like, malty, fermented odor, cocoa	earthy
vo26	alpha-pinene	1.83	−0.98	Fruity, sweet, apple, berry, ripe tropical notes	fruity
vo40	2-methylpropan-1-ol	2.27	−0.99	Breathtaking, sweet, sweaty-chemical; fermented, whiskey-like in dilution	sweet
vo63	3-methylbutan-1-ol	2.28	−1.00	Breathtaking, alcoholic odor; in dilution a winey-brandy taste	alcoholic
Beef-specific					
vo22	butane-2,3-dione	2.14	−0.83	Strong, buttery odor and taste on dilution	creamy
vo90	methyl 2-hydroxy-propanoate	1.67	−0.90	fresh, fruity	fruity
vo73	3-methylbut-3-en-1-ol	2.27	−0.92	Alcoholic-breathtaking, fusel-like odor with a burning taste	alcoholic
vo7	methyl acetate	2.29	−0.94	Sweet, volatile ethereal-fruity odor	fruity
vo92	2-methyloctan-3-one	1.67	−0.95	mushroom like	earthy
vo98	butan-2-ol	1.67	−0.95	Fermented, fusel-alcoholic notes, oily wine-like,	alcoholic
vo95	pent-3-en-2-ol	1.67	−0.95	Sharp and acetone-like	sharp
vo58	methyl heptanoate	1.67	−0.95	Faint, waxy, sweet odor; nearly tasteless; creamy mouthfeel	creamy
vo116	heptan-1-ol	2.43	−1.00	Weak, fresh, green, fatty odor	green
vo56	methyl hexanoate	2.45	−1.00	Ethereal fruity (pineapple-apple) odor; sweet fruity taste	fruity

[a] Odor descriptions were described based on commercial library (Flavor-Base, 2020, Leffingwell & Associates) and references (Bott & Chambers IV, 2006; Perez-Santaescolastica et al., 2022).
[b] VIP, variable importance in the projection.
[c] pcorr, the correlation coefficient value of variable importance.

aroma characteristics were identified.

Raw meats typically have a little or no flavor and are described as having a “bloody taste” Khan et al., 2015). Similarly, in this study, livestock protein materials had the lowest number of volatile compounds compared to other protein materials. However, distinct aromatic characteristics were revealed using the OPLS-DA model when compared with other materials. Among the livestock protein materials, pork presented the highest alcoholic characteristics, along with green, fruity, earthy, floral, and sweet aroma characteristics. For beef, the selected compounds exhibited alcoholic, green, earthy, and sharp aroma characteristics.

4. Conclusion

In this study, the profile of volatile components, which were highly associated with sensory characteristics, was investigated, and specific volatile compounds and their flavor characteristics related to protein materials were found. There might be an insufficiency in expressing actual sensory aspects because the interpretation was conducted based only on chemical information, excluding the flavor threshold of each compound. However, it has provided the overall flavor characteristics of each protein material by considering the quantitative and common flavor properties of the compounds. This can be effectively applied as valuable fundamental scientific information for developing precise flavor targets in the creation of alternative foods. It can also be used as the basis information for identifying the source of off-flavors in alternative food products. Furthermore, extending the findings of this study to research changes in flavor influenced by various factors in food processing could contribute the development of food products using alternative protein materials.

CRediT authorship contribution statement

Min Kyung Park: Writing – review & editing, Writing – original

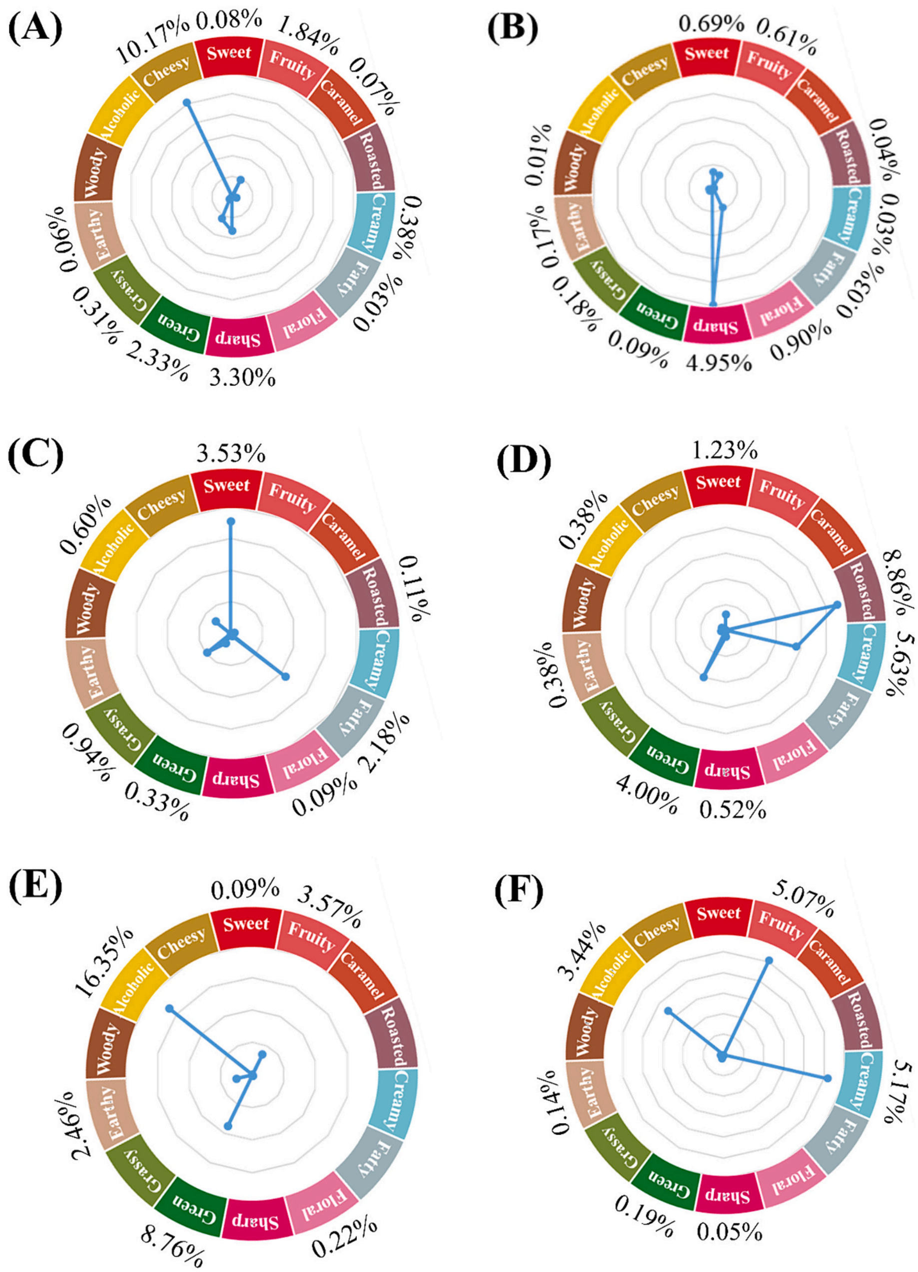

Fig. 3. Protein materials-specific aroma characteristics of: (A), TM, *Tenebrio molitor*; (B), PB, *Protaetia brevitarsis seulensis*; (C), TVP, Textured vegetable protein; (D), TPP, Textured pea protein; (E), Pork; (F), Beef. The numbers outside the circle show the quantitative ratios of volatile compounds in each odor category compared to the total volatile components.

draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Dong-Min Shin:** Methodology, Formal analysis. **Yun-Sang Choi:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101570.

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