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Review

Edible insects as sustainable food sources: extraction techniques, nutritional profiles, and volatile characteristics

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Abstract: Edible insects have gained considerable attention as sustainable and nutrient-rich protein sources in the food industry. This review summarizes key advancements in edible insect protein and oil extraction techniques. Efficient protein recovery techniques are discussed. In addition, strategies such as defatting (which enhances extraction efficiency) are also discussed. The nutritional significance of edible insect-derived peptides, amino acids, and fatty acids is also reviewed, with emphasis on their potential as food ingredients. Analytical techniques for characterizing edible insect volatile compounds are described, along with the key identified volatiles. Furthermore, fermentation has been explored as a strategy to enhance the consumer acceptance of edible insects. These insights support the development of innovative and sustainable food products that utilize edible insect resources.

Key words: edible insect, sustainable resources, extraction technique, nutritional characteristic, volatile profile

1. Introduction

Edible insects have garnered significant research interest because of their uses in various sectors, including the food industry.[1] Compared to conventional livestock, they require fewer resources, such as water and land, while emitting lower levels of CO_2 and ammonia.[2] Consequently, edible insects are regarded as a promising alternative food source for achieving the United Nations (UN) Sustainable Development Goals (SDGs). As the global population is projected to reach approximately nine billion by 2050, concerns regarding the sufficiency of food supply continue to rise.[3] The Food and Agriculture Organization (FAO) has recognized edible insects as a sustainable and nutritious food source for human consumption.[4] Currently, more than 2,100 species of edible insects are consumed by approximately two billion people across more than 113 countries.[5] As the market for edible insects continues to expand, they are increasingly being recognized as a valuable food source.

Currently, thirty-five African countries, Mexico, China, Thailand, and India, have been identified as major consumers of edible insects, demonstrating the

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greatest levels of species diversity. Furthermore, twenty-nine countries in Asia, twenty-three in the Americas, fourteen in Oceania, and eleven in Europe have been documented as regions where edible insects are widely consumed.[6] Beetles (Coleoptera, 31 %) are the most commonly consumed edible insects, followed by caterpillars (Lepidoptera, 18 %), bees, wasps, and ants (Hymenoptera, 14 %), and grasshoppers, locusts, and crickets (Orthoptera, 13 %). Other consumed groups include Hemiptera (10 %), termites (Isoptera, 3 %), dragonflies (Odonata, 3 %), flies (Diptera, 2 %), and various others (5 %).[6] The European Union (EU) maintains strict regulatory frameworks regarding the use of edible insects.[7] Nevertheless, research is ongoing on their potential as food and pet feed, especially using *Hermetia illucens*, *Tenebrio molitor*, and *Bombyx mori*.[6] In Croatia and Italy, maggot cheese has traditionally been regarded as a delicacy. In several African countries, edible insect consumption primarily relies on traditional harvesting from natural habitats. Across Asia, edible insects with reported anticancer and immunomodulatory effects are being utilized in the development of functional food products.[8]

The bioavailability of edible insect-derived proteins is comparable to that of soybeans, indicating that they are readily digested and absorbed in the human body.[9] In addition, they aid various biological activities, including anti-inflammatory effects, alleviation of abdominal pain, and immune system enhancement.[9,10] Edible insect-derived proteins are being actively explored for additional functional properties. Furthermore, insect oil is obtained as a by-product of the defatting process employed for protein extraction.[11] Edible insect oils are a good source of essential fatty acids, such as α-linolenic acid and linoleic acid.[2] Therefore, oil derived from edible insects has the potential to contribute to the development of high value-added technologies and serve as a valuable upcycling resource.

Volatile compounds are key contributors to food quality, as they enhance the sensory experience of eating.[12] Hence, the volatile profile of foods significantly influences consumer acceptance.[13,14] Therefore, to promote the utilization of edible insects in the food industry, the establishment a comprehensive dataset on their volatile compound profiles is essential. Moreover, the impact of processing methods such as fermentation on volatile compounds should be analyzed, given that fermentation is widely used to improve both the volatile profile and safety of foods.[15] Therefore, this review investigates the key volatile compounds in edible insects and the changes in their volatile profiles resulting from fermentation.

The growing interest in edible insects has inspired research on them across various fields. However, comprehensive literature detailing the extraction methods, nutritional composition, and volatile profiles of edible insects is limited. This review highlights the potential of edible insects as a sustainable food source, covering the various extraction methods for proteins and oils. Additionally, the nutritional composition of amino acids and fatty acids, along with key volatile compounds and the effects of fermentation, is also presented.

2. Edible Insect Protein Analysis and Characterization

2.1. Methods for edible insect protein extraction

Edible insects are recognized as a rich source of dietary protein, with protein content ranging from 31.06 % to 71.04 %.[9] Efficient protein extraction from edible insects is highly dependent on the choice of extraction method, with factors such as solvent type and intrinsic protein characteristics playing key roles.[16] Selecting an appropriate extraction method is crucial for optimizing protein yield and functionality.[17-19] The protein yields obtained using different extraction techniques are presented in *Table* 1.

Defatting is a common step in edible insect protein extraction and is typically performed using organic solvents to enhance the efficiency. This process has been shown to improve protein yield, as demonstrated in *Protaetia brevitarsis* larvae, where defatting increased the protein yield from 68.77 % to 77.62 %.[20] Hexane is a widely used degreasing solvent, effectively removing over 96 % of oil and enhancing the functional

Table 1. Techniques for extracting proteins from different edible insects

Edible insect species	Extraction solution	Protein yield (%)	Reference
Alphitobius diaperinus	6 M NaOH/1 M HCl	62.32	[17]
Allomyrina dichotoma	0.02 % (w/v) ascorbic acid+0.58 M saline solution	65.12	[16]
Acheta domesticus	6 M NaOH/1 M HCl	61.23	[17]
Apis mellifera	0.1 M NaOH	55.20	[19]
Locusta migratoria	6 M NaOH/1 M HCl	58.17	[17]
Protaetia brevitarsis	1.1 mol/L potassium iodide	77.62	[20]
Protaetia brevitarsis	distilled water	77.62	[22]
Schistocerca gregaria	0.1 M NaOH	57.50	[19]
Tenebrio molitor	6 M NaOH/1 M HCl	49.90	[17]
Tenebrio molitor	0.02 % (w/v) ascorbic acid/0.58 M saline solution	76.05	[16]

properties of edible insect proteins.[21,22] Hexane has demonstrated superior protein extraction efficiency, achieving a protein yield of 77.62 %, compared to methanol (70.41 %) and ethanol (68.39 %).[22] After degreasing, edible insect-derived proteins are typically extracted using pH-based solutions such as NaOH and distilled water.[17-22] Protein yields achieved by adjusting the pH using NaOH in various edible insect species were reported as follows: 49.90 % for *T. molitor*, 62.32 % for *Allomyrina dichotoma* larvae, 61.23 % for *Acheta domesticus*, and 58.17 % for *Locusta migratoria*.[17]

In contrast to the conventional methods, some studies have reported successful protein extraction without pH adjustment. Hexane was utilized to defat *T. molitor*, *A. dichotoma*, and *P. brevitarsis*, followed by the rapid extraction of proteins using 0.02 % (w/v) ascorbic acid and 0.58 M saline.[16] Sonication has been reported to enhance protein yields. The protein yield of *Schistocerca gregaria* extracted using NaOH was 52.9 %; however, it increased to 57.50 % using sonication. Similarly, the protein yield of *Apis mellifera* from sonification (55.20 %) was higher compared to that from NaOH extraction (39.60 %). This highlights that improved protein recovery is achieved when sonication is used instead of solvent-based extraction methods.[19]

Ethanol treatment during protein extraction enhanced the functional properties of the proteins. The freeze-dried *T. molitor* larval powder was initially defatted using hexane and subsequently dissolved in distilled water to achieve a concentration of 10 %. The pH was adjusted using NaOH, and ethanol was added to the supernatant. This treatment facilitated the breakdown of high-molecular-weight proteins into low-molecular-weight proteins, accompanied by structural modifications such as a reduction in the proportion of α-helices and an increase in β-sheets.[18]

These results highlight the importance of selecting appropriate processing methods for optimizing protein recovery. Protein yield varies significantly depending on the edible insect species and processing conditions applied. For example, the effectiveness of pH adjustment and solvent selection varies between species: NaOH treatment yielded 49.90 % in *T. molitor* and 62.32 % in *Alphitobius diaperinus* larvae.[17] These differences emphasize that for maximizing the protein yield, appropriate extraction methods must be selected, depending on the characteristics of each edible insect species.

2.2. Peptide profiling

In edible insects, peptides are the basic units that constitute the proteins. Sequence analysis is essential to understand the structural and functional properties of edible insect proteins. However, studies on edible insect-derived peptides are limited due to structural changes caused by thermal processes during sterilization and storage.[23] Consequently, establishing a comprehensive database of edible insect-derived peptides is essential to support further research.

Peptide analysis is an important approach for identifying edible insect species and exploring their functional properties. Peptide profiling of *A. domesticus*

was performed using ultra-performance liquid chromatography coupled with quadrupole time-of-flight mass spectrometry (UHPLC-QTOF-MS/MS). Four peptide sequences specific to the *Acheta* genus were identified: AAELSGDAQTAVR, QQFPDGAQAADK, VQEAVQPHADAVAESLK, and LSNHLSNLFK. These peptides are considered potential authentication markers for the identification of *A. domesticus*.[24] Furthermore, peptides with angiotensin-converting enzyme (ACE) inhibitory activity (which contribute to blood pressure regulation) have been identified in *T. molitor* larvae. Reversed-phase high-performance liquid chromatography (RP-HPLC) analysis revealed peptide sequences such as Tyr-Ala-Asn, YAN, NIKY, QGLGY, and HILG.[25,26] In addition, four ACE inhibitory peptides (SY, PF, YPY, and WI) were identified in *P. brevitarsis* larvae.[27] These peptides promote vasodilation and help reduce blood pressure.[25]

2.3. Amino acid compositions

The amino acid profile offers valuable insights into the nutritional value, protein conversion efficiency, and potential functional properties of edible insect proteins.[22] Amino acid analysis of insects is conducted using an amino acid analyzer. The amino acid content varies based on the preprocessing methods, such as freeze-drying and defatting. The amino acid compositions of the edible insects are listed in *Table* 2.

The major amino acids identified in *A. domesticus* were alanine (80.52 – 222.21 mg/g), glutamic acid (37.72 – 99.51 mg/g), and glycine (47.21 – 93.73 mg/g). *A. domesticus* contains various essential amino acids (EAAs) such as proline and aspartic acid, along with other amino acids vital for human health.[28,29]

Table 2. Amino acid profiles (mg/g) of three edible insects

Amino acid	*Allomyrina dichotoma*	*Acheta domesticus*	*Bombyx mori*	*Hermetia illucens*	*Protaetia brevitarsis*	*Tenebrio molitor*
Essential amino acid						
Histidine	5.19–72.56	-	27.00–29.50	0.44–0.49	2.37–16.25	2.97–17.16
Isoleucine	8.51–37.70	23.70–35.41	33.00–34.00	0.51–0.56	2.54–14.18	3.17–9.18
Leucine	12.40–28.50	45.00–64.84	48.90–62.00	0.84–0.87	3.69–14.55	5.58–9.95
Lysine	10.70–42.12	46.14–51.52	50.00–61.00	0.44–0.69	4.28–18.00	5.11–15.26
Methionine	0.93–2.51[1]	11.48–11.77	12.50–34.00	0.28–0.29	1.19–4.79[1]	0.71–2.98[1]
Phenylalanine	12.20–48.50[2]	18.58–23.69	28.40–46.00	0.57–0.74	12.56–36.06[2]	7.93–13.41[2]
Tryptophan	-	2.81–18.48	6.80–15.00	0.12–0.13	-	-
Threonine	6.09–29.51	14.86–32.90	28.40–39.00	0.39–0.43	3.18–21.98	2.55–5.96
Valine	8.78–58.35	41.53–55.02	39.80–47.00	0.58–0.63	3.11–22.03	3.67–11.34
Non-essential amino acid						
Alanine	5.99–41.90	80.52–222.21	39.00–40.90	0.51–0.55	3.06–32.71	3.26–12.63
Arginine	5.22–18.87	-	43.20–47.00	0.45–0.46	2.36–28.12	3.04–5.18
Aspartic acid	13.38–53.60	16.77–77.43	6.10–91.00	0.12–1.19	4.98–39.55	5.97–12.50
Cysteine	-	-	9.10–14.00	0.04–0.10	-	-
Glutamic acid	24.45–495.00	37.72–99.51	95.00–102.30	0.11–1.07	10.17–73.88	10.37–44.64
Glycine	9.25–92.20	47.21–93.73	36.00–58.00	0.41–0.42	4.70–46.75	3.69–14.15
Proline	14.70–104.83	51.91–84.26	35.20–70.00	0.45–0.51	12.18–184.33	6.59–80.30
Serine	6.99–25.64	7.56–47.21	37.00–38.60	0.32–0.37	4.73–22.37	2.26–5.26
Tyrosine	-	-	34.10–56.00	0.65–0.83	-	-
Reference	[16], [33]	[28], [29]	[34], [35]	[30], [31]	[32], [33]	[16], [33]

[16], [22], [33], and [34] used freeze-dried and defatted edible insects powder; [28], [29], and [32] used fresh weight of insects; [30] used microwave-dried and defatted edible insects powder; and [31] used oven-dried and defatted edible insects powder.
[1]Total methionine and cysteine content
[2]Total phenylalanine and tyrosine content

In the case of *H. illucens,* the predominant amino acids identified were glutamic acid (0.11 – 1.07 mg/g), aspartic acid (0.12 – 1.19 mg/g), and leucine (0.84 – 0.87 mg/g), along with methionine, cysteine, and tryptophan.[30,31] The FAO has reported that the recommended intake of sulfur-containing amino acids (in particular methionine and cysteine) is 2.30 % for children, adolescents, and adults.[32] Therefore, *H. illucens* is a suitable dietary source of sulfur-containing amino acids.[30]

The amino acids in freeze-dried *P. brevitarsis* larvae showed the highest contents of glutamic acid (10.17 – 73.88 mg/g), aspartic acid (4.98 – 39.55 mg/g), and proline (12.18 – 184.33 mg/g). In addition, EAAs, including histidine, isoleucine, and leucine, have also been identified.[22,33] These EAAs are not capable of being synthesized by the human body; therefore, their intake is crucial for proper nutrition and is strongly recommended.[35] Similarly, the major amino acids identified in *A. dichotoma* and *B. mori* are glutamic acid, aspartic acid, and proline.[13,33-35]

The major amino acids identified in freeze-dried *T. molitor* larvae are proline (6.59 – 80.30 mg/g), glutamic acid (10.37 – 44.64 mg/g), and phenylalanine (7.93 – 13.41 mg/g). Moreover, it includes several essential amino acids such as lysine and valine, which are important for human health.[13,33]

Edible insects contain high levels of glutamic acid (0.11 – 495.00 mg/g) and aspartic acid (0.12 – 91.00 mg/g). These values are comparable to those in beef, with glutamic acid at 75.10 mg/g and aspartic acid at 41.10 mg/g.[36] Similar levels have also been reported in fish (pomfrets), which contains 114.00 mg/g of glutamic acid and 76.00 mg/g of aspartic acid.[37] The edible insect protein has a well-balanced amino acid profile, with EAAs such as lysine, which are not available in grains, tubers, and legumes.[38]

Moreover, amino acids contribute to the development of tastes such as umami, bitterness, and sweetness, thereby significantly influencing the sensory properties of food.[39] Umami provides a savory sensation and enhances the overall intensity of other tastes.[40] Among the amino acids contributing to umami taste, glutamic acid and aspartic acid have been identified as predominant in edible insects, similar to their abundance in beef, pomfrets, and soybeans.[30,31,36,39] Methionine, an amino acid known to be associated with bitter taste, is abundant in soybeans but only present in trace amounts in edible insects.[41] Methionine content could potentially contribute to differences in bitterness between soybeans and edible insects. Therefore, edible insects are considered to exhibit sensory properties comparable to those of conventional protein sources such as meat, fish, and soybeans.

Hydrophobic amino acids, valine, alanine, isoleucine, and leucine, facilitate antioxidant activities.[42] Furthermore, leucine, arginine, phenylalanine, proline, and alanine are responsible for hypoglycemic activities.[43] In addition, glutamic acid, alanine, isoleucine, tryptophan, methionine, phenylalanine, proline, and valine are important amino acids for facilitating lipid metabolism.[44] In particular, glutamic acid plays a crucial role in nitrogen metabolism, as it participates in nitrogen assimilation and serves as a key component in aminotransferase reactions.[45] Aspartic acid contributes to the production of EAAs, such as lysine, threonine, methionine, and isoleucine, through metabolic pathways.[43] Hence, insufficient levels of these EAAs are associated with a potential increase in the risk of obesity, cardiovascular diseases, headaches, immune disorders, and other related health conditions.[46] Accordingly, edible insects rich in balanced amino acids offer a valuable dietary resource and hold potential in supporting human nutrition.

3. Edible Insect Oil Extraction and Fatty Acid Compositions

3.1. Extraction methods for edible insect oils

Lipids account for the second-largest portion of the nutritional composition of edible insects, with a higher content observed during the larval stage.[5] The larvae of *T. molitor* are extensively studied edible insects. Techniques such as Soxhlet extraction, solvent extraction (SE), three-phase partitioning (TPP), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and ultrasound-assisted extraction (UAE) have been employed to extract lipids from

Table 3. Lipid extraction techniques from *Tenebrio molitor*

Extraction technique	Extraction solvent	Oil yield (%)	Reference
Soxhlet	ethanol	41.72	[47]
SE	n-hexane	29.24	[11]
TPP	t-butanol	24.62	[47]
SFE	CO_2	25.43	[2]
PLE	ethanol	32.37	[49]
UAE	ethanol	28.85	[49]
UAE	ethanol	26.99	[2]

SFE, supercritical fluid extraction; TPP, three-phase partitioning; PLE, pressurized liquid extraction; UAE, ultrasound-assisted extraction; SE, solvent extraction.

edible insects. The oil content of *T. molitor* larvae ranges from 25.43 to 41.72 % (*Table* 3). The yield of edible insect oil is dependent on the extraction method used. A detailed explanation of each method is provided in this section.

The Soxhlet method has demonstrated the highest oil extraction efficiency (41.72 %) compared to other techniques.[47] However, this conventional method has certain limitations, such as requiring a large volume of solvent and involving prolonged extraction at high temperatures.[22] Similarly, the n-hexane-based SE method achieves relatively high yields (29.24 %) and is widely employed in industrial oil extraction due to its high oil selectivity, ease of evaporation, and low energy demands.[11] However, concerns regarding human health and environmental safety have been raised during the extraction process.[48]

The TPP technique induces phase separation based on ammonium sulfate concentration, forming three layers: an oil-containing organic phase at the top, a protein-rich layer in the middle, and a hydrophilic layer with polysaccharides at the bottom.[47] Although TPP yields less oil than other methods (24.62 %), it efficiently recovers valuable by-products such as proteins, enhancing its utility. SFE is widely used to extract natural extracts and oils. Supercritical CO_2, with its optimal critical temperature (31.1 °C), prevents thermosensitive compound degradation during extraction.[24] This non-toxic, easily removable method is environmentally sustainable due to CO_2 recovery and reuse.[2]

The extraction yield of oils is dependent on their solubility in the selected solvent.[2] Therefore, to optimize the extraction process, the selection of the extraction solvent should be considered along with the extraction method. A comparison of the oil yields from *T. molitor* larvae using two ethanol-based extraction methods (PLE and UAE) has been reported.[49] The ethanol-based PLE and UAE methods yielded 32.37 % and 28.85 % oil, respectively, both exhibiting high extraction efficiency. PLE is an eco-friendly method that enhances the extraction efficiency by operating at high pressures; this reduces the solvent use and improves the efficiency by decreasing polarity, viscosity, and surface tension.[50,51] UAE is another efficient method that minimizes time and energy consumption. By utilizing acoustic cavitation, UAE enhances cell disruption, thereby improving mass transfer and accelerating compound release.[52]

These findings indicate that edible insects contain considerable amounts of oil extractable through various methods. However, to effectively compare the various extraction methods, it is crucial to consider the edible insect species and the preparation steps performed before oil extraction, such as drying or grinding.

3.2. Fatty acid profiles

The fatty acid profiles of edible insects depend on their diet, sex, and species. Analysis of edible insect fatty acids is commonly performed using gas chromatography coupled with a flame ionization detector (GC-FID). Oleic acid (C18:1) and linoleic acid (C18:2) were the predominant fatty acids identified in several edible insect species, including *T. molitor* larvae, *Gryllus bimaculatus*, and *A. domesticus* (*Table* 4). These fatty acids are predominantly identified in most edible insects.[2,11,47,53-55]

Oleic acid (C18:1), a monounsaturated fatty acid (MUFA) commonly found in olive oil, is recognized for its ability to regulate immune function.[56] It increases the beneficial high-density lipoprotein (HDL) cholesterol concentrations in the blood.[49] The oleic acid content of *T. molitor* larvae (42.11 – 44.55 %) was comparable to that of sesame seed oil (43.00 %), rice bran oil (43.42 %), and palmolein (43.36 %).[57,58] In contrast,

Table 4. Fatty acid profiles (%) of different edible insect species

Fatty acids	*Acheta domesticus*	*Gryllus bimaculatus*	*Tenebrio molitor*
SFA			
C10:0	-	0.00–0.54	0.02–0.40
C12:0	0.00–0.56	0.25–0.60	0.28–0.39
C13:0	-	-	0.00–0.08
C14:0	0.44–1.61	0.87–0.93	3.09–4.03
C15:0	0.00–0.08	0.00–0.11	0.00–0.16
C16:0	25.02–25.55	25.46–28.80	16.53–18.21
C17:0	0.00–0.26	0.00–0.23	0.00–0.19
C18:0	8.62–10.69	7.06–8.15	2.61–3.08
C20:0	0.42–0.61	0.39–0.53	0.05–0.12
C22:0	0.00–0.22	0.00–0.04	0.01–0.01
C23:0	-	-	0.00–0.12
C24:0	0.00–0.17	-	-
MUFA			
C14:1	-	0.00–0.03	0.02–0.02
C16:1	0.57–1.32	1.32–2.30	1.61–2.42
C17:1	0.00–0.05	-	0.00–0.16
C18:1 (trans)	0.00–0.08	0.00–0.21	-
C18:1	24.28–26.30	25.46–32.15	42.11–44.55
C20:1	0.00–0.13	-	0.16–0.28
C22:1	-	0.00–0.01	-
C24:1	-	0.00–0.26	0.00–0.02
PUFA			
C18:2 (trans)	0.00–0.26	0.00–0.16	-
C18:2	30.88–32.82	24.29–32.38	27.61–28.29
C18:3	0.88–1.50	0.91–1.22	1.15–1.35
C20:2	0.00–0.11	0.00–0.16	0.06–0.07
C20:3	0.00–0.10	0.00–0.02	-
C20:4	0.00–0.17	0.00–0.01	-
C20:5	0.00–0.49	-	-
PUFA/SFA	0.90–0.92	0.75–0.86	1.09–1.31
References	[54], [55]	[2], [54]	[2], [11]

SFA, saturated fatty acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid.

G. bimaculatus showed an oleic acid content (25.46 – 32.15 %) similar to that of pumpkin seed oil (28.70 %) and sunflower seed oil (29.50 %),[58] while that of *A. domesticus* (24.28 – 26.30 %) closely matched with that of soybean oil (24.77 %) and sunflower oil (25.92 %).[57] Linoleic acid (C18:2), a type of polyunsaturated fatty acid (PUFA), is primarily present in oils such as safflower, sunflower, and soybean.[57] It also acts as a precursor to arachidonic acid (C20:4), which is crucial for the proper functioning of cells and muscles.[59] α-Linolenic acid (C18:3), a type of PUFA, is predominantly found in flaxseed, canola, and soybean oils.[60] It has diverse health benefits, including cardiovascular protection, anti-obesity, anti-diabetic, anti-inflammatory, anticancer, and antioxidant properties.[61] Essential fatty acids, such as linoleic acid (an omega-6 fatty acid) and α-linolenic acid (an omega-3 fatty acid), must be obtained through the diet since the human body cannot produce them. As shown in *Table* 4, edible insects contain high levels of linoleic acid (24.29 – 32.82 %) and α-linolenic acid (0.88 – 1.50 %), indicating their potential as a valuable source of essential fatty acids. In particular, the α-linolenic acid contents of the three edible insect species were higher than those found in commonly consumed edible oils, including sesame seed, sunflower seed, pumpkin seed, safflower, and rice bran oils.[57,58]

Among the saturated fatty acids (SFAs), palmitic acid (C16:0) and stearic acid (C18:0) were identified as the predominant components. These fatty acids have also been identified as the predominant SFAs in beef tallow and lard.[62,63] Palmitic acid is a key SFA involved in the structural integrity of cellular membranes and the formation of secretory and transport lipids.[64] In addition to its cholesterol-lowering effects on blood lipid profiles, stearic acid has been reported to exert neuroprotective effects against both oxidative stress and excitotoxic neuronal damage.[65]

Furthermore, the polyunsaturated fatty acid to saturated fatty acid (PUFA/SFA) ratio is a key indicator of the dietary impact on cardiovascular health, with higher ratios suggesting greater nutritional value.[66] The PUFA/SFA ratio in *Table* 4 ranged from 0.75 to 1.31, exceeding the recommended minimum ratio of 0.45 for a healthy human diet. Indicators of coronary artery disease risk, such as the arteriosclerosis index (AI) and thrombosis index (TI) (lower values correspond to improved health outcomes), were found to be below 1 in oils derived from *T. molitor* larvae, *G. bimaculatus*, and *A. domesticus*.[2,54,55] Therefore, edible insect oil is a beneficial source for nutritional intake.

4. Characterization of Edible Insect Volatiles and Key Compounds

4.1. Isolation and analysis of edible insect volatiles

Volatile compounds contribute significantly to food quality through their effects on volatile perception.[67] In edible insect studies, several techniques have been applied for the extraction of volatile compounds, including direct solvent extraction, solvent-assisted flavor evaporation (SAFE), and solid-phase microextraction (SPME).[2,68,69] Among these, SPME combined with gas chromatography-mass spectrometry (GC-MS) is the most widely used method. This approach is frequently employed to analyze volatile compounds in edible insects and their extracts (*Table* 5).

SPME is a clean and safe sorption technique because it requires no solvents.[70] It is a cost-effective approach that allows for easy automation and enhanced repeatability.[71] Hence, SPME is one of the most widely used techniques for analyzing volatiles in food. This process involves inserting and exposing the SPME fiber into the headspace, allowing the adsorption of volatile compounds. The analytes were then thermally desorbed at the GC injector port. A more recent method, known as SPME-Arrow, uses an outer tube containing a steel stick with an arrow-shaped tip. The larger diameter and extended length of the sorbent phase and fibers enhance both sensitivity and robustness.[12,67,70] Choosing a suitable fiber coating is crucial for SPME and SPME-Arrow analyses. The suitability of a fiber coating for an analyte depends on the properties of the extraction phase, which affect the selectivity and reliability of the technique.[73] Divinylbenzene-carboxen-polydimethylsiloxane (DVB/CAR/PDMS) is the most commonly used fiber,[2,11,67,72,73] and GC is the most widely employed technique for analyzing pre-extracted volatile compounds. While nitrogen, helium, and hydrogen are commonly employed as carrier gases, helium is the exclusive choice for edible insect volatile analysis (*Table* 5).

4.2. Key volatile compounds in edible insects

Volatile compounds are generated through various intricate reactions, including carbohydrate fermentation and proteolytic and lipolytic processes. In addition, peptides, amino acids, and fatty acids are the key substrates for subsequent reactions, such as oxidation and Strecker degradation.[1] Many volatile compounds have been identified in edible insects. These compounds include acids, alcohols, aldehydes, esters, hydrocarbons, indoles, ketones, and pyrazines. Only the compounds reported in at least three publications are presented in *Table* 6.

Seven aldehydes have been identified in edible insects. Aldehydes (a major class of volatile compounds in edible insects) have a significant influence on the volatile profile, particularly in imparting fatty notes.[2] Aldehydes are categorized into linear, branched, and aromatic types based on their structural characteristics.

Table 5. Analytical conditions for various methods in edible insect volatile profiling

Insect species	Sample type	Extraction condition		GC condition		Reference
		Method	Fiber	Column type	Carrier gas	
Tenebrio molitor	Powder	SPME	DVB/CAR/PDMS	HP-Innowax	Helium	[74]
Tenebrio molitor	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[2], [11]
Locusta migratoria	Powder	SPME	DVB/CAR/PDMS	HP-Innowax	Helium	[75]
Locusta migratoria	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[2]
Protaetia brevitarsis	Defatted powder	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[73]
Protaetia brevitarsis	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[11]
Acheta domesticus	Powder	SPME	DVB/CAR/PDMS	HP-Innowax	Helium	[74]
Allomyrina dichotoma	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[11]
Gryllus bimaculatus	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[2]
Zophobas atratus	Oil	SPME-Arrow	DVB/CAR/PDMS	HP-5MS	Helium	[2]

SPME, solid-phase microextraction; DVB/CAR/PDMS, divinylbenzene-carboxen-polydimethylsiloxane.

Table 6. Common volatile compounds identified in edible insects

Volatile Compound	Aroma description[1]	Insect species	Reference
Acids			
3-methylbutanoic acid	acid, cashew, cheese, fat	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *A. domesticus*	[2], [48], [75]
acetic acid	acid, cheese, fruit, pungent, sour	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae, *A. domesticus*	[2], [48], [73], [74]
butanoic acid	acid, butter, cheese, must, rancid	*T. molitor* larvae, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *A. domesticus*	[2], [48], [75]
hexanoic acid	acid, cheese, fat, fermented, goat	*T. molitor* larvae, *L. migratoria*, *A. dichotoma* larvae, *P. brevitarsis* larvae, *A. domesticus*	[48], [73], [75]
propanoic acid	acid, fat, pungent, rancid, raspberry	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *A. domesticus*	[2], [48], [75]
Alcohols			
2,3-butanediol	cream, floral, fruit, herb	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [48], [73], [75]
ethanol	alcohol, floral, ripe apple, sweet	*T. molitor* larvae, *L. migratoria*, *P. brevitarsis* larvae, *A. domesticus*	[20], [73], [75]
Aldehydes			
2-methylbutanal	almond, burnt, chocolate, cocoa, fermented	*T. molitor* larvae, *G. bimaculatus*, *P. brevitarsis* larvae, *A. domesticus*	[2], [20], [73], [75]
3-methylbutanal	acrid, almond, apple, chocolate, cocoa	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *P. brevitarsis* larvae, *A. domesticus*	[2], [20], [75]
benzaldehyde	almond, berry, bitter, bitter almond, burnt	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [11], [20], [48], [73]
heptanal	citrus, dry fish, fat, green	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *P. brevitarsis* larvae	[2], [20], [73]
hexanal	apple, cut grass, fat, fish, fresh	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [11], [20], [73]
nonanal	citrus, cucumber, fat, floral, green	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *P. brevitarsis* larvae, *A. domesticus*	[2], [20], [75]
phenylacetaldehyde	berry, floral, flower, geranium, honey	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *P. brevitarsis* larvae	[2], [20], [73]
Esters			
ethyl acetate	balsamic, butter, fruit, grape	*T. molitor* larvae, *L. migratoria*, *P. brevitarsis* larvae	[20], [73], [75]
Hydrocarbons			
d-limonene	citrus, lemon, mint, orange	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [11], [20]
ethylbenzene	ethereal, floral, strong, sweet	*T. molitor* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[11], [20], [48], [73]
methylbenzene	bitter almond	*T. molitor* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[11], [20], [73]
o-xylene	geranium, oil, pungent	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae, *A. domesticus*	[2], [11], [20], [48], [73], [75]
p-xylene	cold meat fat, oil, sweet	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [11], [20], [48], [73]
undecane	alkane, wax	*T. molitor* larvae, *L. migratoria*, *A. dichotoma* larvae, *P. brevitarsis* larvae	[11], [73], [75]
Indoles			
indole	animal, burnt, floral	*G. bimaculatus*, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae, *P. brevitarsis* larvae	[2], [48], [73]
Ketones			
2-decanone	fat, fruit, green, melon	*T. molitor* larvae, *G. bimaculatus*, *L. migratoria*, *P. brevitarsis* larvae	[2], [20], [48]
Pyrazines			
2,5-dimethylpyrazine	burnt, cocoa, coffee	*T. molitor* larvae, *L. migratoria*, *Z. atratus* larvae, *A. dichotoma* larvae	[2], [11], [48], [75]

[1]Aroma descriptions were adapted from the VCF online database (https://www.vcf-online.nl/VcfHome.cfm). *T. molitor*, *Tenebrio molitor*; *G. bimaculatus, Gryllus bimaculatus*; *L. migratoria*, *Locusta migratoria*; *Z. atratus*, *Zophobas atratus*; *A. dichotoma*, *Allomyrina dichotoma*; *A. domesticus*, *Acheta domesticus*; *P. brevitarsis*, *Protaetia brevitarsis*.

Linear aldehydes are primarily derived from the oxidative degradation of unsaturated fatty acids such as oleic and linoleic acids, which are abundant in various foods.[74] In particular, nearly half of the aldehydes detected in edible insects belong to this category, with heptanal, hexanal, and nonanal being the most frequently reported.[2,11,20,73,75] In contrast, branched aldehydes are predominantly formed through Strecker degradation and the Maillard reaction.[74] 2-methylbutanal and 3-methylbutanal are the most commonly identified branched aldehydes.[2,20,73,75] Aromatic aldehydes include benzaldehyde and phenylacetaldehyde. These compounds have been identified as key volatile compounds in roasted sesame oil, present in addition to the dominant pyrazines.[76] In addition, phenylacetaldehyde (recognized as a precursor to floral notes) is also associated with the Maillard reaction in nuts and has been identified in freshly roasted almonds.[77]

Six hydrocarbons have been identified. However, due to their relatively high detection thresholds, these compounds are considered to have a minimal impact on the overall volatile profile of edible insects.[1] Hydrocarbons such as d-limonene, o-xylene, and p-xylene have been frequently detected in edible insects and edible insects-derived oils.[2,11,20,48,73,75] Five acids have been reported in at least three studies: 3-methylbutanoic acid, acetic acid, butanoic acid, hexanoic acid, and propanoic acid. Acetic acid was identified in most edible insects.[2,48,73,75] In addition, 2,5-dimethylpyrazine, a compound of the pyrazine group, was detected in various edible insects.[2,11,48,75] This compound has also been identified in several foods, such as peanut oil and roasted sesame oil,[76,78] indicating a strong association with roasted and nutty notes.[76]

4.3. Effect of fermentation on the volatile compounds in edible insects

Consumers still exhibit an aversion to edible insects, possibly due to hygienic concerns and cultural practices.[79] Increasing awareness of appealing volatile compounds, superior nutritional value, and enhanced functionality can improve consumer acceptance of edible insect-based foods.[13] Edible insects exhibit undesirable volatile characteristics, including acidic, cheesy, and rancid notes.[2,48,73,75] Therefore, while processing the edible insects, implementing strategies to effectively control the undesirable volatile characteristics is necessary. Fermentation is recognized as an effective processing method that improves the nutritional, functional, and sensory properties of food products.[80] Fermentation is also utilized to enhance the volatile profiles of edible insects, as it modifies and improves volatile compounds.

Solid-phase fermentation of defatted *P. brevitarsis* larval powder using lactic acid bacteria and yeast was investigated. As a result of fermentation with *Lactococcus lactis*, tetramethylpyrazine (nutty, vanilla, and cocoa) and trimethylpyrazine (cocoa and potato) were formed. In addition, ethyl isovalerate (apple, citrus, and pineapple), isoamyl butyrate (fruity, apricot, and banana), and 2-isobutyl-3-methylpyrazine (herbal, green, and sugar) were detected in the yeast (*Saccharomyces cerevisiae*) fermentation group. These compounds positively influence consumer preferences and have been shown to enhance the volatile profiles of edible insects through fermentation.[13]

Solid-phase fermentation of *A. dichotoma* larval powder using LAB was examined. Before fermentation, indole, 1-octen-3-ol, and 3-octanol were detected in *A. dichotoma* larvae.[12] These are undesirable volatile compounds that exhibit unpleasant characteristics, such as fecal and animal notes, which negatively affect wine quality.[81,82] These levels decreased following the fermentation of *A. dichotoma* larvae with *Lactobacillus acidophilus* and *Lactobacillus plantarum*. In addition, significant amounts of 1-propanol, 2-propanol, and ethanol were detected. These compounds contribute to the sweetness during fermentation.[15]

The effects of the spontaneous and sourdough fermentation of *A. domesticus* powder using *L. plantarum* have also been reported. Spontaneous fermentation resulted in a higher production of benzoic acid (faint and balsam) and disulfide dimethyl (garlic). Sourdough fermentation produces 3-methyl-1-butanol (whiskey, malt, and burnt), 2-methyl-5-propan-2-ylcyclohex-2-en-1-one (minty, caraway, and bread),

and benzaldehyde (almonds and fruits) in addition. These compounds are found in alcoholic beverages, such as baijiu, and contribute to improving consumer acceptance.[83,84] This suggests that fermentation is an effective method for enhancing the volatile profiles of edible insects.[28]

5. Current Applications of Edible Insects in Processed Foods

With the growing global demand for sustainable alternative foods, edible insect-derived ingredients are increasingly being integrated into a variety of processed food products, including snacks, baked goods, and meat analogs. These applications not only aim to enhance nutritional profiles but also to improve environmental sustainability. However, enhancing consumer perception remains a long-term challenge for the edible insect-based food industry. While the consumption of whole, processed edible insects has been prevalent in traditional practices, contemporary consumers demonstrate a stronger preference for edible insect-derived ingredients in powdered or visually unrecognizable forms.

Appropriate processing technologies, such as the formulation of composite fortified foods with edible insect powder and other ingredients, facilitate the effective integration of edible insects into conventional food products. Several studies have demonstrated the potential of edible insect-based ingredients as viable alternatives to traditional protein sources. For example, burgers made with mealworm-based patties received higher ratings in taste and overall acceptability than fully plant-based alternatives, suggesting positive consumer receptivity toward edible insect-derived meat substitutes.[85] Similarly, the incorporation of yellow mealworm powder into maize tortillas significantly enhanced the protein content of the final product.[86] Recent advances have even demonstrated the feasibility of using 4D printing technology to create edible snacks enriched with cricket powder.[87] Furthermore, supplementing cookies with edible insect powders—such as *T. molitor* larvae, *P. brevitarsis* larvae, and *G. bimaculatus*—has been shown to enhance crude protein content while maintaining favorable sensory qualities.[88] The inclusion of silkworm pupae in Frankfurt sausage formulations has likewise resulted in improved protein levels and enhanced textural properties compared to control samples.[89] These diverse applications underscore the versatility of edible insects as food ingredients, facilitating their broader acceptance and integration into food systems.

5. Conclusion

Edible insects are being increasingly recognized as a sustainable and nutrient-rich alternative protein source, with significant potential in the food industry. This review examines the techniques for extracting proteins and oils from edible insects, emphasizing their efficiency and functionality. Various protein extraction methods, including pH-based solubilization, solvent-based extraction, and ultrasound-assisted techniques, have been evaluated for their effects on protein recovery. Defatting, which is commonly performed using hexane, significantly enhanced protein yield. Additionally, extraction processes involving the use of ascorbic acid and saline solutions have demonstrated improved extraction efficiencies without requiring pH adjustments. SFE, PLE, and UAE have been identified as eco-friendly and efficient oil extraction techniques. The compositional characteristics of edible insect-derived peptides and amino acids were also discussed. In particular, bioactive peptides with ACE inhibitory activity were identified in *T. molitor* and *P. brevitarsis* larvae, indicating their potential as functional food ingredients. Furthermore, the fatty acid composition of edible insects, particularly the presence of essential fatty acids such as linoleic acid and α-linolenic acid, emphasizes their nutritional value. The polyunsaturated to PUFA/SFA ratio in edible insect oils exceeded the recommended dietary threshold, reinforcing their role in promoting cardiovascular health. The characterization of edible insect volatiles revealed the role of various compounds in influencing the volatile profiles. Techniques such as SPME-GC-MS, particularly with the improved sensitivity of SPME-Arrow, have been widely employed

for volatile profiling. Key volatile compounds, including aldehydes, hydrocarbons, acids, and pyrazines, were identified. In particular, fermentation modifies the volatile profiles of edible insects by generating desirable volatile compounds, suggesting its potential to enhance the sensory quality of edible insect-based food products.

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