Highlights

- Consumer acceptance of a new food is dependent on sensory properties.
- High variability of volatile compounds among insect species.
- Greater content of volatile lipid oxidation compounds after drying treatments.
- More compounds from Maillard reaction and Strecker pathway after roasting.

Abstract

Background: Sensory properties are essential in introducing a new food since they largely determine consumer acceptance. In previous years, edible insects were the focus of attention of many studies due to their relatively recent incorporation in the Western human diet. Expanding the analysis and understanding of flavour compounds facilitates food product design and compiling the available information can help further advances in this area.

Scope and Approach: Analytical methods applied to determine volatile compounds in edible insect samples are reviewed, and a comprehensive overview of the volatile compounds identified is provided. A total of 406 compounds were found (see ST1), classified into different chemical families: linear hydrocarbons, aromatic and cyclic hydrocarbons, aldehydes, ketones, esters, alcohols, carboxylic acids, pyrazines, other nitrogenous compounds, sulphur compounds, phenols, terpenes and furans. In addition, those compounds that were reported by more than one author are presented in more detailed tables.

Key Findings and Conclusions: Significant variability of volatile compounds has been observed among species, and a clear influence of processing on the development of the final aroma profile was established. A higher content of lipid oxidation compounds was noted after drying treatments, as well as a higher number of Maillard and Strecker pathway compounds after roasting. Particular techniques such as defatting or fermentation could be applied to remove or reduce unpleasant odours typical for some insects. Given the complexity of the study, this review may be helpful for further research on the characterisation and improvement of edible insect flavour.

Keywords: Volatile compounds, edible insects commercialisation, flavour chemistry, chromatography

The flavour of edible insects: a comprehensive review on volatile compounds and their analytical assessment

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1. Current perspective on edible insect flavour

Recently, edible insects attracted the interest of many researchers because of their broad application potential in various sectors, including the feed and food industry. The demand for novel protein sources and sustainability considerations have driven a deep interest in their application in feed and human food. They have been studied as animal feed because of their reduced environmental impact compared to conventional protein sources such as soybean meal and fishmeal (Sánchez-Muros *et al.*, 2014). As most existing literature indicates, edible insects are considered a sustainable and economical food source. They require little space, feed and water, generate low greenhouse gas emissions and are easy to process (Zielińska *et al.*, 2018). However, limitations include variability in nutritional value, the difficulty of large-scale production and the production of defence secretions (Verkerk *et al.*, 2007).

Although more than 2000 types of insects have been consumed by humans for centuries worldwide (Ramos-Elorduy *et al.*, 1997; Garofalo et al., 2019; Baiano, 2020), only a few have been recognised as edible in Western areas due to the limited knowledge available concerning edible insects. In addition, in many countries, especially in the West, consumers have a negative attitude regarding insect consumption. Nevertheless, we do not realise that every person indirectly consumes around 500 g of insects per year on average, as insect-derived ingredients and additives can be found in many food products (Zielińska et al., 2018). For instance, carmine (E120), a red colourant commonly used in food, is dervied from the cochineal (*Dactylopius coccus*) and the cheese called casu marzu contains 8 mm long larvae (Verkerk *et al.*, 2007; Zielińska *et al.*, 2018). The resistance of many consumers towards eating insects currently compromises the commercialisation of whole edible insects. Therefore, it is essential to use alternative forms of presentation to enable their progressive inclusion into the regular diet. Common strategies that could reduce consumer rejection include using edible insect flours or incorporating isolated edible insect components in food products, thereby rendering the insect invisible (Zielińska *et al.*, 2018). Edible insects are a good source of protein, essential fatty acids, antioxidants, minerals and vitamins. In addition, edible insect protein isolates also provide techno-functional properties such emulsifying, foaming and gelling capacity. As such, they can contribute to the production of dairy drinks, dressings, desserts, cheese or tofu (Tzompa Sosa & Fogliano, 2017). In addition, bioactive peptides from edible insects provide biological properties such as antimicrobial, antioxidant, antihypertensive and immunomodulatory properties, which are valuable in health promotion and food preservation (Tzompa Sosa & Fogliano, 2017).

Even though the flavour of edible insects can be described as tasty, buttery, sweet, herbal or crunchy, it is still not sufficient to motivate consumers who are averse to insect consumption. Appearance and odour must be considered as well, since it is widely known that these attributes are determining factors for consumers in deciding whether or not to try a product. Flavour varies among species and can be affected by the development stage, feed, and preparation method. The latter is a fundamental factor in the development of the final flavour due to the chemical changes that occur during heating (Żołnierczyk & Szumny, 2021). In this respect, it is clear that processing and cooking methods substantially affect insect flavour. It has been observed that scalded edible insects are almost tasteless, while roasting results in organoleptic changes and enhanced palatability (Jeon *et al.*, 2016; Kouřimská & Adámková, 2016). Fermentation is an innovative technology with great application potential in the edible insect industry. For example, sauces from *Galleria mellonera* and *Locusta migratoria* have been obtained through fermentation, with higher consumer ratings regarding sweetness, acidity, bitterness and umami compared to traditional fish sauces (Mouritsen *et al.*, 2017). These processes were shown to improve not only the taste but also the rheological and textural properties, the functionality of bioactive compounds and the shelf life of the products obtained (Hasan *et al.*, 2014).

Processing can modify the final product flavour, either positively or negatively affecting consumers' attitude. Therefore, considering that the sensory properties are essential when commercialising new food products, understanding the complex taste and flavour of edible insects and the impact of processing is vital to improve consumer acceptance of insect-derived foods. In this regard, FAO (Food and Agriculture Organization) decided to promote their consumption as an alternative sustainable food for human consumption. More and more restaurants are offering edible insects as a gourmet dish (van Huis *et al.*, 2013; Verkerk *et al.*, 2007), and more research is being focused on it. However, many studies carried out so far on edible insects have mainly focused on their nutritional composition.

In contrast, there is a lack of knowledge on the organoleptic characteristics, which are essential when introducing a novel food into the diet of reluctant consumers. Table 1 summarises studies that have been conducted concerning the organoleptic properties of edible insects and edible insect-based products using surveys or tasting sessions. On a more fundamental level, it is essential to understand the chemical nature of the aroma compounds involved. An overview of studies in this domain is provided in Table 2. Analysing and understanding the compounds involved in the flavour of edible insects should be the main focus of attention. This could result in a better food product design, improving consumers' acceptance. Therefore, this review aims to compile all currently available information on volatile compounds in edible insects and provide the necessary data for further studies. To this end, different techniques used to isolate edible insect volatile compounds are collected in this review, together with procedures for their separation, identification and quantification. In addition, a comprehensive study of volatile compounds identified in edible insects is presented.

2. Methods for analysis of volatile compounds in edible insects

The increasing interest in insects as an alternative protein source requires the development of reliable methods to assess their quality. However, volatile compound analysis is complicated due to the wide range of factors affecting their analysis, including the large number of compounds involved, their different chemical characteristics and volatility, as well as potential effects of the matrix on their release. Existing analytical techniques exhibit a varying extractive power and selectivity for each compound, resulting in varying volatile profiles (Sghaier *et al.*, 2016). A variety of techniques have been reported for the extraction of volatiles from edible insects, including solid-phase microextraction (SPME), simultaneous distillation extraction (SDE) and supercritical fluid system extraction (SFE). In addition, extraction conditions applied vary considerably, as seen in Table 3. However, in all studies gas chromatography is applied. Although not described in the field of edible insects, the use of other methods such as high-pressure liquid chromatography (HPLC) could be an alternative, especially for aldehyde analysis, for which good results have been obtained in other food products (Antequera *et al.*, 1992; Reindl & Stan, 1982).

Sampling

The most common procedure for collecting edible insect samples is randomly collecting them from wild harvests, specialised edible insect rearing companies or edible insect shops. Following collection, edible insects are usually starved for 24 h, 48 h, or even 72 h (Kim *et al.*, 2021), before being killed by freezing at -20 °C or, less commonly, -50 °C (Haber *et al*., 2019a) or -80 °C (Cheseto *et al.*, 2020). In the study conducted by Ssepuuya *et al.* (2020), insects were placed in self-sealing bags before freezing.

Analyses of volatile compounds in edible insects have been carried out on whole insect samples (Khatun *et al.*, 2021; Kröncke *et al.*, 2019; Mahattanatawee *et al.*, 2018; Shen *et al.*, 2006; Yeo *et al.*, 2013; Żołnierczyk & Szumny, 2021), on samples without wings and legs (Ssepuuya *et al.*, 2020, 2021), on samples without the head, wings and legs (Kiatbenjakul *et al.*, 2015) or on particular anatomical parts, such as glands (Kiatbenjakul *et al.*, 2014). On the other hand, edible insect powders (Mishyna *et al.*, 2020; Nissen *et al.*, 2020), oil extracts (Cheseto *et al.*, 2020; Tzompa-Sosa *et al.*, 2019) and protein isolates and hydrolysates (Grossmann *et al.*, 2021; Lee *et al.*, 2021) have been studied. In the latter studies, the impact of their addition as an ingredient in particular food products on the overall volatile profile was examined.

Insects are solid and heterogeneous materials. Hence volatile compounds could differ from one insect to another and can be affected by the feed and the season in which they are sampled (Haber et al., 2019a). In addition, processing operations and conditions applied (blanching, drying, etc.) greatly affect the volatile profile (Khatun et al., 2021; Ssepuuya et al., 2021).

Isolation

Several methods for extracting volatiles have been developed so far, but only a few have been used for studying edible insects and derived products, which are discussed below.

Solid-phase microextraction (SPME) before gas chromatography-mass spectrometry (GC-MS) analysis has been the most widely used method so far to analyse volatile compounds in edible insects and edible insect-based products. Complete quantification of volatiles is difficult with this technique, but it enables comparison of relative amounts of compounds among samples when using the same analytical procedure (Hospital *et al.*, 2012).

SPME is a clean and safe sorption technique because no solvents are needed. In addition, it is cheap, simple and fast since it can be easily automated, thereby increasing repeatability (Bojko *et al.*, 2012). Therefore, it is one of the most widely used techniques for analysing volatiles in food. It was developed by Arthur & Pawliszyn (1990). It consists of a sample pre-concentration step that allows the volatiles present in the headspace to be sorbed by the fibre for later liberation. Extraction is performed in an oven using samples placed in glass vials, ensuring a homogeneous temperature of the sample and the headspace. Analyte sorption is performed by insertion and exposure of the SPME fibre to the headspace, followed by thermal desorption of the analytes at the injector port of the gas chromatograph. Among the existing fibres, divinylbenzene-carboxen-poly(dimethylsiloxane) (DVB/CAR/PDMS) coated fibres are most abundantly used due to their extensive coverage.

A recently developed technique called HS-SPME Arrow consists of an outer tube in which an arrow-headed steel stick is inserted, coated with a sorbent material similar to the classical SPME. The sorbent phase and the fibres are larger in diameter and length, resulting in increased sensitivity and robustness. To date, it has only been used in a few studies on food, among which only Lee *et al.* (2021) have applied it to isolated edible insect proteins.

Traditionally, steam distillation, often followed by organic solvent extraction, has been used to isolate volatile substances from food. Using a special fast, simple and efficient distillation unit designed by Likens & Nickerson (1964), the condensation of a steam distillate and an immiscible extraction solvent can be carried out simultaneously, a technique known as Simultaneous Distillation Extraction (SDE). This apparatus provided a substantial concentration of the volatiles and reduced the use of organic solvents. Schultz *et al.* (1977) modified the design offered by Likens and Nickerson by improving the distillation and extraction conditions while reducing the processing time, allowing to shorten the exposure of the sensitive substances to heat. Yeo et al. (2013) used this modified Likens-Nickerson apparatus to extract volatile compounds from *Protaetia brevitarsis* larvae prior to GC-MS analysis.

An alternative clean (solvent-free), fast and safe method is extraction with supercritical fluids (SFE). This technique generally consists of three stages (Bcwadt & Hawthorne, 1995). The first stage involves the isolation of the analytes from the matrix and their migration into the supercritical fluid. This step mainly determines the analyte recovery from heterogeneous matrices. The second stage consists of the elution of the analyte from the extraction cell and depends on the fluid flow rate, the sample size and the solubility of the analyte. Finally, the third step, collecting the analyte from the SFE capture system, is the most specific phase and largely depends on the restriction and capture systems used. The main advantage offered by this method is the ability to vary the solubilisation power by adjusting the pressure and temperature, allowing to apply it on a wide variety of analytes with different polarity characteristics and molecular sizes. The most commonly used supercritical fluid is CO_2, as its low critical temperature allows the extraction of thermally unstable substances. In addition, it provides an oxygen-free environment which reduces potential oxidation of the analytes (King, 1990). In edible insect analysis, this method has only been used by Shen *et al.* (2006), who extracted aromatic compounds from edible Chinese black ants through the use of supercritical CO_2 at a constant flow rate of 8 kg/h, using an extraction vessel temperature of 50 °C at 30 MPa, and a liberation vessel temperature of 45 °C at a pressure of 8 MPa.

Other isolation methods have been applied by only a limited number of authors. For example, Li *et al.* (2009), macerated the samples in hexane for organic compounds extraction before chromatographic analysis. On the other hand, Cheseto *et al.* (2020) used dichloromethane Super-Q traps to trap the volatiles from the samples under vacuum conditions.

Gas chromatography

Gas chromatography is the most commonly used technique for analysing pre-extracted volatile compounds. Using this technique, compounds are separated based on a difference in affinity to a polymer coating of a capillary column through which they are passed. Therefore, the choice of the column, more specifically its stationary phase (from low to high polarity), influences the resolution of the peaks obtained. An extensive range of columns exists, as seen in Table 3. Some authors used apolar columns with a stationary phase of 5% phenylmethyl polysiloxane. Non-polar stationary phases exhibit a longer shelf life compared to polar phases. Furthermore, low-bleed columns (ms) usually have higher temperature limits and, being more inert, offer the possibility to analyse a broader range of analytes. Instead, others used highly polar stationary phases such as ZB-WAX, composed of polyethylene glycol.

On the other hand, in addition to the stationary phase, also the column dimensions affect the quality of the results. Thus, diameter influences efficiency, retention, pressure, carrier gas flow rate and capacity. The length influences efficiency, retention (analysis time) and carrier gas pressure. Film thickness affects retention, resolution, bleed, inertia and capacity. The most frequently used lengths include 30 and 60 m; only Nissen *et al.* (2020) used a 50 m column. The diameter chosen in most studies was 0.25 mm, although Grossmann *et al.* (2021), Nissen *et al.* (2020), Tzompa Sosa & Fogliano (2017), and Mahattanatawee *et al.* (2018) used a larger diameter (0.32 mm). In the case of film thickness, a broader range was applied, with thicknesses ranging from 0.2 to 1 µm, 0.25 µm being the most widely used.

Although the most commonly employed carrier gases for gas chromatography, in general, are nitrogen, hydrogen and helium, helium was used in all studies collected in this review. In addition, splitless injection mode was most commonly used by authors who study edible insects, but split injection mode has also been used, with a splitting ratio of 1:20 by Patrignani *et al.* (2020) and Kim *et al.* (2021), 1:10 by Yeo *et al.*, (2013) and 1:1 by Shen *et al.*, (2006).

Identification and quantification

There are several ways to identify compounds. The use of at least two identification methods is required, including the use of reference compounds (Cheseto *et al.*, 2020; Haber et al., 2019a; Khatun *et al.*, 2021; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Li *et al.*, 2009; Mahattanatawee *et al.*, 2018; Yeo *et al.*, 2013), literature comparison (Haber et al., 2019a; Lee *et al.*, 2021; Li *et al.*, 2009; Ssepuuya *et al.*, 2020, 2021; Żołnierczyk & Szumny, 2021), and/or using library databases such as Wiley (Haber et al., 2019a; Indriani *et al.*, 2021; Lee *et al.*, 2021; Li *et al.*, 2009; Nissen *et al.*, 2020; Shen *et al.*, 2006), NBS 98 (National Bureau of Standards) (Shen *et al.*, 2006), Fiehn (Kim *et al.*, 2021) and NIST (National Institute of Standards and Technology) (Alagappan *et al.*, 2021; Cheseto *et al.*, 2020; Grossmann *et al.*, 2021; Haber et al., 2019a; Khatun *et al.*, 2021; Kiatbenjakul *et al.*, 2014, 2015; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Nissen *et al.*, 2020; Olarte Mantilla *et al.*, 2020; Sánchez *et al.*, 2021; Ssepuuya *et al.*, 2020, 2021; Tzompa-Sosa *et al.*, 2019; Yeo *et al.*, 2013; Żołnierczyk & Szumny, 2021). Quantification of volatile compounds, on the other hand, is mainly done by assessing the individual relative percentages through the area normalisation method, which is a semi-quantitative approach (Haber et al., 2019a; Kröncke *et al.*, 2019; Li *et al.*, 2009; Mishyna et al., 2020; Nissen *et al.*, 2020; Shen *et al.*, 2006; Yeo *et al.*, 2013). Few authors, e.g. Lee *et al.* (2021), performed quantification by comparing the peak area of the compounds to the peak area of internal standards.

3. A description of the volatile compounds found in edible insects

Volatile compounds arise from numerous complex reactions, including carbohydrate fermentation and proteolytic and lipolytic processes. In addition, both (free) fatty acids, amino acids and peptides serve as substrates for further reactions such as oxidation, Strecker and Maillard processes, which are greatly affected by processing, especially by thermal treatments. As a result, various volatile compounds with different olfactory thresholds are generated, providing different aromatic characteristics to the final food product. Besides that, spices and other additives used during processing constitute an additional source of volatiles.

The effect of different processing techniques on the volatile profile of edible insects and their impact when added as an ingredient to other processed foods have been studied abundantly. Several authors reported many volatile compounds in edible insects and edible insect-based products. These compounds include linear hydrocarbons, branched hydrocarbons, aromatic and cyclic hydrocarbons, aldehydes, ketones, esters and ethers, alcohols, carboxylic acids, pyrazines, other nitrogenous compounds, sulphur compounds, phenols, terpenes, furans, lactones and chloro compounds. Nevertheless, only a limited number of these volatile compounds substantially contribute to the overall aroma.

In this review, we only describe the compounds reported in edible insects or products derived exclusively from edible insects. In contrast, studies describing volatiles from foods to which insects were added are excluded, since these volatiles may originate from the food matrix rather than from the added insects, hence the natural origin of these volatile compounds cannot be assured. According to that, 406 volatile compounds have been reported in different edible insects listed in the Supplementary Table (ST.1). The table also includes information on the sensory attributes associated with some of the volatile compounds. However, some volatiles have not been associated with an aroma description, so their influence on the final aroma is not yet known. In addition, the contribution of compounds to the aroma depends on their concentration and detection threshold. As can be seen, many volatile compounds are found in many edible insect species. Still, many of these compounds have only been observed by one author. In this review, only those compounds that have been reported in more than one publication are shown in the Tables described below.

A total of 36 aldehydes have been observed in edible insects (ST.1), of which 18 were reported by multiple authors (Table 4). Linear aldehydes may result from the oxidative degradation of unsaturated fatty acids, mainly oleic acid, linoleic acid and arachidonic acid, which are abundant fatty acids in foods (Whitfield & Mottram, 1992). Almost half of the aldehydes detected in edible insects were linear aldehydes, of which hexanal, octanal and nonanal were the most commonly reported (Alagappan *et al.*, 2021; Grossmann *et al.*, 2021; Haber et al., 2019a; Khatun *et al.*, 2021; Kim *et al.*, 2021; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Ssepuuya *et al.*, 2020). On the other hand, branched aldehydes originate mainly from Maillard reactions and Strecker degradation (Whitfield & Mottram, 1992). The most commonly detected branched aldehydes were 2-methylbutanal, 3-methylbutanal and benzaldehyde (Alagappan *et al.*, 2021; Grossmann *et al.*, 2021; Haber et al., 2019a; Khatun *et al.*, 2021; Kim *et al.*, 2021; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Mishyna et al., 2020; Żołnierczyk & Szumny, 2021). Differences in the aldehyde profile and content in edible insect samples have been observed between different drying methods: sun drying, freeze-drying, microwave drying and oven drying (Khatun *et al.*, 2021; Kröncke *et al.*, 2019; Li *et al.*, 2009; Mishyna et al., 2020). Higher hexanal and 2-methyl propanal contents were detected in freeze-dried samples indicating that freeze-drying may increase sensitivity to lipid oxidation, whereas oven-drying may have a protective effect due to the inactivation of lipoxygenase enzymes (Khatun *et al.*, 2021; Mishyna et al., 2020). Nevertheless, compared to raw materials, all drying methods resulted in a higher content of aldehydes formed through Strecker degradation, such as 2-methylbutanal and 3-methylbutanal (Kröncke *et al.*, 2019), providing a wide variety of aromas such as buttery, toasty, fatty, floral, sweet or roasted. Concerning unsaturated aldehydes, the compounds (E)-2-nonenal, (Z)-2-nonenal and (E)-2-decenal-4,5-epoxy have been found in samples of *Tenebrio molitor* and *Lethocerus indicus* (Grossmann *et al.*, 2021; Kiatbenjakul *et al.*, 2015; Mahattanatawee *et al.*, 2018), suggesting that these edible insects may exhibit a metallic flavour due to their aromatic potency, particularly of (E)- and (Z)-2-nonenal (Kiatbenjakul *et al.*, 2015).

The number of ketones observed in edible insects reaches 42 (ST.1), of which 14 were reported by multiple authors (Table 5). Only a few 2-methylketones and acetoin have been reported by three or more authors (Grossmann *et al.*, 2021; Haber et al., 2019a; Khatun *et al.*, 2021; Kiatbenjakul *et al.*, 2015; Kim *et al.*, 2021; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Ssepuuya *et al.*, 2020; Tzompa-Sosa *et al.*, 2019; Żołnierczyk & Szumny, 2021). Thermal treatments such as roasting applied after boiling resulted in increased concentrations of 2-methyl ketones (Ssepuuya *et al.*, 2020). The 2-methyl ketones are produced by β-oxidation of lipids and β-keto decarboxylation of acids (Shahidi & Oh, 2020). Thus, defatting the samples significantly reduces their content and could therefore reduce unpleasant odours (Lee *et al.*, 2021). Despite the above, it has been noted that 2-butanone was formed upon a yeast fermentation process with *Saccharomyces cerevisiae* and was associated with a pleasant fruity flavour. Therefore, yeast fermentation has been suggested as a process that could improve the overall flavour of some edible insect species (Kim *et al.*, 2021). On the other hand, β-iodone, which has been identified in samples of *L. indicus*, *Acheta domesticus* and *T. molitor*, and whose origin can be attributed to thermal degradation of carotenoids (Kawakami *et al.*, 1991), is a compound with significant aromatic impact, providing floral notes such as violet or raspberry.

A total of 43 alcohol compounds were found (ST.1), of which ten were reported by multiple authors (Table 5). Among the most commonly detected alcohols, 1-hexanol, 2-ethyl-1-hexanol, and 1-octen-3-ol have been reported by three or more authors (Alagappan *et al.*, 2021; Grossmann *et al.*, 2021; Khatun *et al.*, 2021; Kiatbenjakul *et al.*, 2014, 2015; Kim *et al.*, 2021; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Tzompa-Sosa *et al.*, 2019) (Table 5). 1-Octen-3-ol was described to significantly affect the aroma by contributing to a characteristic mushroom odour. Lee *et al.* (2021) reported that the concentration of this odour-active volatile is reduced by defatting the samples. This technique could improve the final aroma by preventing the appearance of other off-flavours. 1-octen-3-ol, together with 2-methyl-1-propanol and 3-methyl-1-butanol, have been described as fermentation by-products, which in the case of insects could be related to microbial activity of the gut microflora (Tzompa-Sosa *et al.*, 2019). In line with this, Kim *et al.* (2021) observed a significant increase in the number of alcohols in samples of *Allomyrina dichotoma* when fermentation processes with *S. cerevisiae* were applied.

A total of 30 carboxylic acids have been reported (ST.1), of which 12 were reported by multiple authors (Table 6). However, only four have been found in at least four studies: 2-methylbutanoic acid, 3-methylbutanoic acid, butanoic acid and hexanoic acid (Alagappan *et al.*, 2021; Grossmann *et al.*, 2021; Khatun *et al.*, 2021; Kiatbenjakul *et al.*, 2014, 2015; Kröncke *et al.*, 2019; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Sánchez *et al.*, 2021; Tzompa-Sosa *et al.*, 2019). Butanoic acid and other acids such as 2-methylpropanoic acid may, similar to alcohols, originate from fermentation processes by bacteria, and other compounds, such as pivalic acid (2,2-dimethylpropanoic acid) and propanoic acid are derived from microbial metabolism (Řezanka *et al.*, 2012). In addition, Li *et al.* (2009) also observed a remarkable increased amount of acids in black ant samples after sun-drying, suggesting that these compounds may result from hydrolytic rancidity caused by high temperatures and enzyme activity. The aromatic contribution of this group is mainly undesirable, as their odours are described as rotten, faecal or pungent. Among them, valeric acid (or pentanoic acid) is primarily responsible for the unpleasant odour characteristic of *Blaptica dubia*, which according to Tzompa-Sosa *et al.* (2019) is even perceptible during the extraction of its oil. On the other hand, 60 esters have been found in edible insects (ST.1), of which ten were reported by multiple authors (Table 6) (Haber et al., 2019a; Kiatbenjakul *et al.*, 2014, 2015; Kim *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020). Ethyl acetate, (E)-2-hexenyl acetate, (E)-2-heptenyl acetate and (E)-2-hexenyl butanoate were found in three or more studies. These esters may either be formed through esterification of carboxylic acids and alcohols, or may be naturally present (Khatun *et al.*, 2021). Authors have suggested that esters from short-chain acids provide fruity odours, whereas esters from long-chain acids result in fatty odours. Furthermore, ethyl esters generally have a lower detection threshold than methyl esters (Dominguez *et al*., 2019). Based on the above, the presence of compounds such as ethyl oleate and ethyl hexadecanoate in *P. brevitarsis* powder (Yeo *et al.*,2013), or methyl dodecanoate, methyl tetradecanoate and methyl hexadecanoate in dried *Gryllus assimilis* and *A. domesticus* samples (Khantun *et al*., 2021) could result in a remarkable fatty flavour. On the other hand, it has also been found that (E)-2-hexenyl acetate and (E)-2-hexenyl butanoate are the most intense aroma compounds present in the glands of the edible male giant water bug, *L. indicus* (Kiatbenjakul *et al.*, 2014). In addition, it has been observed that oven drying and, above all, blanching reduce their contents, probably due to the use of high temperatures since these volatiles are thermo-sensitive. (Khatun *et al.*, 2021; Yeo *et al.*, 2013). A total of 80 hydrocarbons have been detected (ST.1), of which 14 were reported by multiple authors (Table 7). Even though hydrocarbons constitute the most numerous family of volatiles detected in edible insects, most of these compounds have a high odour detection threshold. Therefore, their contribution to the overall aroma of foods is considered to be limited (Carrapiso *et al.*, 2010). Among the 36 linear and 31 branched hydrocarbons listed (ST.1), only two linear hydrocarbons have been reported by more than three authors, *i.e.* undecane and tridecane (Alagappan *et al.*, 2021; Haber et al., 2019a; Kim *et al.*, 2021; Li *et al.*, 2009; Mishyna et al., 2020; Sánchez *et al.*, 2021). A total of 13 cyclic and aromatic hydrocarbons have been reported (ST.1), among which only styrene and ρ-xylene have been reported by two authors (Cheseto *et al.*, 2020; Lee *et al.*, 2021), while only one author has reported the remaining hydrocarbons. The most probable origin of hydrocarbons relates to lipid oxidation and Maillard reactions (Shahidi & Oh, 2020). Apart from that, it has been observed that hydrocarbons present in insect glands could be part of defensive secretions released in alarm situations, or could function as solvents and controlled-release substrates for other more volatile compounds such as aldehydes (Gunawardena & Herath, 1991). In this regard, a high content of n-tridecane has been observed in the glands, which functions as a deterrent in synergy with other aromatic substances (Marques *et al.*, 2007). Other defence compounds have been found in large amounts in larvae and pupae bees, including decane, undecane and dodecane (Haber et al., 2019a). In addition, Singer (1998) indicated that most of the hydrocarbons found in edible insects are cuticular compounds involved in species recognition and play an important role in insect societies, for example, in finding a mate. Hydrocarbon composition may be affected by the life stage, especially in insects such as bees, as the kind and amount of pollen ingested varies according to the developmental stage, affecting the flavour. This was confirmed by Haber, Mishyna, Itzhak Martinez, *et al.* (2019), who found a significantly increased concentration of ocimene in larvae compared to pupae. This compound is characterised by a pleasant tropical flavour (ST1). Among the 21 pyrazines listed (ST.1), only seven were reported by several authors, with 2,5-dimethyl pyrazine being the most frequently detected (Table 7) (Grossmann *et al.*, 2021; Khatun *et al.*, 2021; Kiatbenjakul *et al.*, 2015; Kim *et al.*, 2021; Kröncke *et al.*, 2019; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018; Mishyna et al., 2020; Sánchez *et al.*, 2021; Żołnierczyk & Szumny, 2021). 2,5-Dimethylpyrazine is responsible for burning smell, and its content increases with increasing roasting temperature (Żołnierczyk & Szumny, 2021). Pyrazines are mainly formed by Maillard reactions, especially during heating processes, and are considered to provide a cooked flavour to food. Maillard reactions have been described as inhibitors of lipid oxidation (Osada & Shibamoto, 2006), therefore, higher contents of pyrazines in oven-dried or blanched samples are correlated with lower amounts of lipid oxidation comounds compared to freeze-dried samples (Khatun *et al.*, 2021). As a result, it has been suggested that Maillard reactions could reduce undesirable odours typical for some edible insects, such as the fishy aroma of, among others, crickets (Capponi, 2016). Additionally, pyrazines, in general, are used as flavour and aroma enhancers, and their presence in high amounts in heat-treated edible insect samples could represent a new source for their natural production (Żołnierczyk & Szumny, 2021). In contrast, there are also nitrogenous compounds whose contribution to the overall flavour is unpleasant. That is the case for indole, a compound which, at low concentration, provides floral notes, but as the concentration increases, the flavour turns into faecal notes (Bensafi *et al.*, 2002). Among the 24 other nitrogen compounds that have been detected in different types of edible insects (ST.1), only two have been reported by several authors (Table 7). Indole, a compound that has been identified in two studies (Grossmann *et al.*, 2021; Kim *et al.*, 2021), is responsible for the unpleasant flavour of the beetle called *A. dichotoma*, although its content and the associated odour can be reduced through fermentation (Kim *et al.*, 2021).

On the other hand, 18 sulphur compounds have been identified (ST.1). As can be observed in Table 7, three of them were reported by several authors, of which 2-acetyl-2-thiazole and methional are the compounds identified by most authors within this group of volatiles (Grossmann *et al.*, 2021; Kiatbenjakul *et al.*, 2015; Lee *et al.*, 2021; Mahattanatawee *et al.*, 2018). Male giant water bug scent glands reportedly contain a substantial amount of 3-sulfanylhexyl acetate (Kiatbenjakul *et al.*, 2014), while the presence of this compound in pheromones has not been confirmed in other insects. Compounds such as dimethyl sulphide and dimethyl trisulfide may indicate microbial spoilage since their origin most likely relates to the action of microbial enzymes on amino acids such as methionine or cysteine. These compounds increased in roasted samples after 8 h of storage, even though roasting is a thermal treatment that inactivates vegetative microorganisms. It is possible that remaining spores germinate once conditions are favourable, resulting in such an increase (Ssepuuya *et al.*, 2021).

Other compounds identified in edible insect samples include seven ethers, 17 phenols, 12 terpenes, 8 furans, 5 lactones and 3 chloro compounds (ST.1). Still, only two phenols, three terpenes and three furans were reported by two or more authors (Table 7). The presence of the phenols such as ρ-cresol (Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2014, 2015; Kim *et al*., 2021) is noteworthy since this compound may be a possible carcinogen. It is a natural metabolic product that is highly toxic, even at low concentrations. It may act as a promoter of stomach tumours and can have adverse effects on the cardiovascular system, central nervous system, lungs, liver, and kidney (ATSDR, 1990). In contrast, limonene, a terpene that may be derived from the ingestion of plants by insects (Ahmad & Beg, 2013), presents beneficial health properties such as hypocholesterolemic, anticarcinogenic and antioxidant properties. In insects, this compound can act against bugs predation (Li *et al*., 2009; Mishyna et al., 2020; Palazzo & Setzer, 2009). Among the furans, 2-pentylfuran has been reported by up to 5 authors (Khatun *et al.*, 2021; Kim *et al.*, 2021; Kröncke *et al.*, 2019; Mishyna et al., 2020; Ssepuuya *et al.*, 2020). This compound was identified as a by-product of the oxidation of linoleic acid and other n-6 fatty acids and contributes to pleasant aromas such as sweet, green and fruity (Ssepuuya *et al.*, 2020).

4. Concluding remarks

This paper presents the first comprehensive review of the volatile profile of edible insects. After analysing the existing data, it can be stated that family and species play an essential role in the number, type and amount of aroma compounds and, therefore, in the individual insects' sensory characteristics.

Raw insects usually have a relatively limited flavour but they contain numerous flavour and aroma precursors. Accordingly, processing has a major effect on the flavour, as shown by the higher content of lipid oxidation compounds after drying treatments and the higher number of compounds formed through Maillard reaction and Strecker degradation after roasting compared to the raw insects. In addition, undesirable flavours can be removed by processes such as defatting or fermentation. At the same time, desirable flavours can be increased through processing and could contribute to the overall aroma by masking the undesirable ones.

On the other hand, edible insects can be used not only as food but also as an ingredient in producing other food products. For example, addition of edible insect powder in bakery products such as biscuits and brownies has been studied extensively. To a much lesser extent, insects have been used in protein-rich food products such as hamburgers or sausages, which could be considered an interesting future line of research. It can be concluded that more species-specific research is needed to understand the edible insect characteristics and the effect of processing, in order to improve their sensory characteristics. These insights could provide information on their potential use in more food products. As such, edible insects could become more attractive to consumers.

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Table 1. Summary of studies carried out to improve the organoleptic knowledge about edible insects.

Goal	**Product**	**Edible insect used***	**Ref**
Consumer acceptance	Muffins	*Gryllodes sigillatus* and *Tenebrio molitor*	(Zielińska *et al*., 2021)
		Tenebrio molitor and *Locusta migratoria*	(Çabuk, 2021)
	Crackers	*Macrotermes bellicosus*, *Syntermes soldiers* and *Brachytrupes* spp.	(Akullo *et al*., 2018)
		Acheta domesticus	(Tuccillo *et al*., 2020)
	Bread	*Tenebrio molitor*	(Barsics *et al*., 2017)
		Acheta domesticus	(Osimani *et al*., 2018)
		Alphitobius diaperinus	(Roncolini *et al*., 2020)
		Schistocerca gregaria	(Haber *et al*., 2019b)
		Locusta migratoria	(Althwab *et al*., 2021)
		Tenebrio molitor and *Alphitobius diaperinus*	(Garciá-Segovia *et al*., 2020)
		Acheta domesticus	(Nissen *et al*., 2020)
	Oatmeal balls	Grasshopper (*n.e.*) and *Tenebrio molitor*	(Chow *et al*., 2021)
	Cupcakes	*Phyllophaga rugosa* and *Nudaurelia melanops*	(Aguilera *et al*., 2021)
	Cake	*Patanga succincta* L.	(Indriani *et al*., 2020)
	Cookie	*Tenebrio molitor*	(Lucchese-Cheung *et al*., 2021)
		Acheta domesticus	(Biró *et al*., 2020)
		Rhynchophorus phoenicis Fabricius	(Ayensu *et al*., 2019)
	Brownies	*Acheta domesticus* and *Gryllodes sigillatus*	(Gurdian *et al*., 2021)
	Bars	*Acheta domesticus*	(Cicatiello *et al*., 2020)
		Acheta domesticus and *Gryllodes sigillatus*	(Ribeiro *et al*., 2019)
	Tortilla chips	*Acheta domesticus*	(Cicatiello *et al*., 2020)
	Extruded rice	*Gryllodes sigillatus* *Locusta migratoria*	(Tao *et al*., 2017)
	Focaccia bread	*Acheta domesticus*	(Tuccillo *et al*., 2020)
	Burgers	*Tenebrio molitor*	(Schouteten *et al*., 2016; Tan *et al*., 2017a)
	Meatballs	*Tenebrio molitor*	(Tan *et al*., 2017b)
	Dairy drink	*Tenebrio molitor*	(Tan *et al*., 2017b)
	Pasta	*Bombyx mori*	(Biró *et al*., 2019)
	Durum wheat pasta	Cricket (*n.e.*)	(Duda *et al*., 2019)
	Cooked edible insect	*Tenebrio molitor*, *Acheta domesticus*,	(Caparros Megido *et al*., 2014)
		Cricket, cockchafer, bamboo worm and bug grasshopper (*n.e.*)	(Halloran *et al*., 2015)
	Buns	Cricket (*n.e.*)	(Pambo *et al*., 2018)
	Protein powder	*Acheta domesticus*	(Barton *et al*., 2020)
	Dried edible insect	*Acheta domesticus* and Tenebrio molitor	(Cicatiello *et al*., 2020)
Sensory evaluation	Egg pasta	*Tenebrio molitor* and *Locusta migratoria*	(Çabuk & Yılmaz, 2020)
	Cookie	*Schistocerca gregaria* and Ruspolia differens	(Cheseto *et al*., 2020)
	Protein isolates	*Acheta domesticus* and Tenebrio molitor	(Grossmann *et al*., 2021)
	Brood	*Apis mellifera*	(Evans *et al*., 2016)
		Schistocerca gregaria	(Haber *et al*., 2019b)
	Frankfurter	*Tenebrio molitor*	(Choi *et al*., 2017)
	Broth	Cricket (*n.e.*)	(Farina, 2017)
	Fermented sauce	*Galleria mellonera* and *Locusta migratoria*	(Mouritsen *et al*., 2017)
	Edible insect	*Tenebrio molitor*	(Wendin *et al*., 2019)
		Tenebrio molitor and *Acheta domesticus*	(Sipponen *et al*., 2018)

n.e., species not specified

Table 2. Studies in which aroma compounds are analysed.

Product	**Edible insect**	**Goal**	**Main findings**	
Cookies edible insect-based and insect powder	*Schistocerca gregaria* *Ruspolia differens*	To identify the volatiles profile and fatty acids that contribute to the aroma of baked goods made with edible insect oils.	Loss in edible insect oil-based biscuits of volatile compounds (comparing to regular biscuits) which contribute to sweet flavours, including 3-methylbutanoic acid, 2-methylbutanoic acid and 2,3-butanediol.	(Cheseto *et al.*, 2020)
	Bombyx mori	To compare the effects of different drying methods, including freeze-drying, microwave drying and oven drying on the volatile composition of edible insect powders and cookies based on them	Microwave drying showed a higher content of pyrazine and pyrrole compounds, as well as the appearance of the "roasted" odour characteristic of Maillard reactions. Oven-dried edible insect powder samples showed herbaceous and fishy odours. The total number of volatile compounds in cookies with 15% of the wheat replaced by dried edible insects was significantly lower compared to pure dried edible insects.	(Mishyna *et al.*, 2020)
Bread	Cricket (species not specified)	To evaluate new gluten-free sourdough breads for celiac community and for responding to the demand for new protein sources.	The samples made with cricket powder were reported to have a fermentation rate similar to that of a standard dough. No differences in acetoin and acetate content were observed, however the ethanol and lactate content was moderately higher whilst the 1,4-butanediol content was slightly below the standard dough. A typical flavour was observed mainly due to its content of 2,4-nonadienal, hexanoic and nonanoic acid, (E,E) 1-hexanol, 1-heptanol and 1-octen-3-ol, 2,4-butanedione, 2-heptanone and 3-octen-2-one.	(Nissen *et al.*, 2020)
Protein isolated	*Protaetia brevitarsis*	To investigate the effects of n-hexane defatting on edible insect larvae protein properties.	Reduced levels of compounds from lipid oxidation such as alcohols and aldehydes and some hydrocarbons with a negative impact on the general flavour were observed, whereas the level of pleasant flavouring hydrocarbons was reported to be increased.	(Lee *et al.*, 2021)
Protein hydrolysates	*Acheta domesticus* and *Tenebrio molitor*	To explore the effect on flavour characteristics caused by enzymatic hydrolysis of protein, to gain additional knowledge on potential flavour of edible insect proteins.	Thirty-eight compounds were identified as active contributors to odour, showing that hydrolysis significantly increases the flavouring power of edible insect proteins.	(Grossmann *et al.*, 2021)
	Cricket powder (non-specified species)	To assess the potential of using yeast strains for producing powder hydrolysates to be used as food ingredients.	The hydrolysates produced by *Debaryomyces hansenii* DB were characterised by the presence of acetic acid and short-chain fatty acids, while those obtained by *D. hansenii* SP6L12 were characterised by methylpyrazine and acetic acid pentyl esters after 72 h incubation. Furanones and ketones were found in the hydrolysates from *Yarrowia lipolytica* PO11 and samples from *Y. lipolytica* RO25 showed pyrazine, ethanol, ketones, lactones, furanones and 2,3-dimethyl-thiophene, whose sensory impact is negative when high concentrations are present.	(Patrignani *et al.*, 2020)

Product	Edible insect	Goal	Main findings	
Oils	*Tenebrio molitor* *Alphitobius diaperinus* *Acheta domesticus* *Blaptica dubia*	To determine the aromatic profile of edible insect-based oils for possible use as an ingredient.	*T. molitor* oil, *A. diaperinus* oil and *A. domesticus* oils have valuable aroma compounds for food applications, but *B. dubia* oil exhibits off-flavour compounds.	(Tzompa-Sosa *et al*., 2019)
Edible insect as food and food ingredient	*Polyrhachis vicina* Roger	To determine the changes in the volatiles composition after sun drying.	After sun drying, lower amounts of ketones and hydrocarbons and higher amounts of carboxylic acids were found, together with the formation of aldehydes.	(Li *et al*., 2009)
	Allomyrina dichotoma	To identify volatiles to related to off-flavour of the larvae and the effect of fermentation process on the improvement of the overall flavour.	The fermentation of *A. dichotoma* powder showed a marked reduction of faecal odour volatiles whereas the fruity flavour volatiles increased. Hence, it could be possible to assume that yeast fermentation processes applied after insect cultivation may be an effective way to improve the flavour of edible insects.	(Kim *et al*., 2021)
	Apis mellifera	To examine differences between two rearing stages (larvae and pupae) and the effect of sugar-supplemented feeding.	Principal volatile compounds representing differences between larvae and pupae were hydrocarbons, corresponding to pheromones, even though their flavour contribution is limited. The odour active compounds included ocimene, diacetyl, dimethylsulphide, nonanal and 2- and 3-methylbutanal.	(Haber *et al*., 2019a)
	Lethocerus indicus	To identify the active odorant compounds in the scent glands, in particular sulphur compounds.	Identification of 3-sulfanylhexyl acetate and 3-sulfanyl-1-hexanol, low-threshold thiol volatiles thought to contribute characteristic cat and ripe guava odours to the overall aroma.	(Kiatbenjakul *et al*., 2014)
		To determine active aromatic compounds of fresh frozen and salt-boiled male giant bugs.	Esters and acids were the main and strongest odorants in all samples, with (E)-2-hexenyl acetate and (E)-2-hexenyl butanoate being the most abundant. Only in salt-boiled samples 2-acetyl-1-pyrroline and 2-acetyl-2-thiazoline were detected.	(Kiatbenjakul *et al*., 2015)
	Ruspolia differens	To investigate the effect of different thermal processing methods.	Boiling increased hexanal and 2-pentylfuran concentrations by more than 80 % whilst limonene was reduced by half. Roasting, in contrast, increased the concentrations of heptanal, octanal, nonanal and 2-ketones.	(Ssepuuya *et al*., 2020)
		To understand the mechanisms of spoilage in order to extend its shelf-life.	Raw samples spoiled at high a_w showed volatile sulphur compounds related to microbial spoilage whereas spoiled samples at low a_w showed aldehydes, ketones and acids, suggesting oxidative rancidity.	(Ssepuuya *et al*., 2021)
	Patanga succincta L.	To evaluate the effects of defatting samples with hexane and the impact of fortifying bakery products with its powder.	The conventional powder showed, compared to the defatted powder, a lower variety of volatile compounds containing more unpleasant flavours, especially of hormones and compounds from lipid oxidation.	(Indriani *et al*., 2021)
	Acheta domesticus and *Gryllus assimilis*	To understand the impact of various drying methods.	Freeze-dried samples showed a higher content of volatile compounds compared to oven-dried and blanched samples. Fatty acid oxidation volatiles were higher in freeze-dried samples, whereas the products of the Maillard reaction were higher in oven-dried samples	(Khatun *et al*., 2021)

Product	Edible insect	Goal	Main findings	
	Musca domestica	To understand the effect of microencapsulation.	After encapsulation of the samples, out of the 22 volatiles initially present, only 4 were detected resulting in the decrease of off-flavours which are typical of edible insect foods.	(Sánchez *et al*., 2021)
	Tenebrio molitor	To compare the effects of freeze-drying, vacuum drying and oven drying.	The freeze-dried and vacuum-dried samples resulted in a higher number of compounds from Maillard reaction and lipid oxidation.	(Kröncke *et al*., 2019)
	Tenebrio molitor and *Zophobas morio*	To investigate the impact of roasting at different temperatures, including 160, 180 and 200 °C.	Treatments at 180 °C were characterized by a pleasant and desirable bread odor, while temperatures of 200 °C showed undesirable burnt flavors derived from the presence of 2,5-dimethylpyrazine.	(Żołnierczyk & Szumny, 2021)
	Protaetia brevitarsis	To analyse the composition of *P. brevitarsis* to verify the potential application as a source of lipids.	By far the greatest number of volatile compounds were acids, followed by esters and hydrocarbons. Principal volatile components were n-hexadecanoic acid, 9-hexadecenoic acid and 6-octadecenoic acid.	(Yeo *et al*., 2013)
	Lethocerus indicus	To understand volatile aromatics to determine their potential use as flavour enhancers.	The most intense aroma compound obtained was (E)-2-nonenal, even though the sweet and herbaceous flavour of the samples resulted from the presence of (E)-2-hexenyl acetate.	(Mahattanatawee *et al*., 2018)
	Oecophylla smaragdina	To verify distinctions among different body parts for their use as a potential source of food ingredients.	The ant nest showed that about 50 % of the compounds were carboxylic acids, but also a large number of alcohols and alkanes were found. On the other hand, the gastric part showed the lowest number of volatiles.	(Alagappan *et al*., 2021)
	Polyrhachis vicina	To understand the nutritional characteristics.	Main volatiles were 9-octadecenoic acid, ethyl oleate, cholesterol and n-hexadecanoic acid.	(Shen *et al*., 2006)

Table 4. Most common volatile aldehydes identified in edible insects.

Volatile Compounds	Sensory attribute	Edible insect	Reference
2-Methyl-propanal	Aldehydic, caramel, cocoa, green, malt, nut	Oven dried locust and raw and microwave dried *Bombyx mori*. *Allomyrina dichotoma*, Protein isolates from *Protaetia brevitarsis*	(Kim *et al*., 2021; Lee *et al*., 2021; Mishyna *et al*., 2020)
2-Methyl-butanal	Chocolate, musty, nutty, malty, almond, fermented.	Raw and oven and microwave dried locust and *Bombyx mori*, Freeze dried Australian green ants, oven dried *Acheta domesticus* and *Gryllus assimilis*, rack oven dried, freeze dried and vacuum dried *Tenebrio molitor* larvae. honey bee pupae powders. Protein isolates from *Protaetia brevitarsis. Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Alagappan *et al*., 2021; Grossmann *et al*., 2021; Haber et al., 2019a; Khatun *et al*., 2021; Kröncke *et al*., 2019; Lee *et al*., 2021; Mishyna *et al*., 2020)
2-Methyl-2-butenal	Green, pungent, ethereal, nutty, apple, fruit, grass, solvent	Microwave dried locust and *Bombyx mori.* Protein isolates from *Protaetia brevitarsis*	(Lee *et al*., 2021; Mishyna *et al*., 2020)
3-Methylbutanal (Isovaleraldehyde)	Aldehydic, ethereal, acrid, almond, chocolate, malty, pungent	Raw and freeze, oven and microwave dried locust, raw and oven and microwave dried *Bombyx mori* and rack oven dried, freeze dried and vacuum dried *Tenebrio molitor larvae.* Freeze dried Australian green ants, oven dried *Acheta domesticus* and *Gryllus assimilis*. Honey bee pupae powders. *Protaetia brevitarsis*, *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates. *Allomyrina dichotoma*.	(Alagappan *et al*., 2021; Grossmann *et al*., 2021; Haber et al., 2019a; Khatun *et al*. 2021; Kim *et al*., 2021; Kröncke *et al*., 2019; Lee *et al*., 2021; Mishyna *et al*., 2020)
Pentanal		Freeze dried *Acheta domesticus* and *Gryllus assimilis*, vacuum dried *Tenebrio molitor* larvae	(Khatun *et al*., 2021; Kröncke *et al*., 2019)
Hexanal	Green, apple, fatty, grassy aldehydic, fresh, fruit, oil	Raw and freeze, oven and microwave dried locust and raw and oven and microwave dried *Bombyx mori*, freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis*, rack oven dried, freeze dried and vacuum dried *Tenebrio molitor* larvae. *Tenebrio molitor*, *Alphitobius diaperinus* and *Blaptica dubia* oils. Raw, boiled and roasted *Ruspolia differens. Protein isolates from Protaetia brevitarsis. Acheta domesticus and Tenebrio molitor protein and hydrolysates*	(Grossmann *et al*., 2021; Khatun *et al*., 2021; Kröncke *et al*., 2019; Lee *et al*., 2021; Mahattanatawee *et al*., 2018; Mishyna et al., 2020; Ssepuuya *et al*., 2020; Tzompa-Sosa *et al*., 2019)
Benzaldehyde	Fruity, sweet, bitter almond, burnt sugar, cherry, malt, roasted, pepper	Microwave dried locust and raw and microwave dried *Bombyx mori*, Roasted *Tenebrio molitor* and *Zophobas morio*, freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis*. *Allomyrina dichotoma*. Protein isolates from *Protaetia brevitarsis*	(Khatun *et al*., 2021; Kim *et al*., 2021; Lee *et al*., 2021; Mishyna *et al*., 2020; Żołnierczyk & Szumny, 2021)
Heptanal	Citrus, fat, green, nut, floral, dry fish	Vacuum dried *Tenebrio molitor* larvae. Raw, boiled and roasted *Ruspolia differens.* Protein isolates from *Protaetia brevitarsis*	(Kröncke *et al*., 2019; Lee *et al*., 2021; Ssepuuya *et al*., 2020)
Benzeneacetaldehyde (Phenylacetaldehyde)	Berry, geranium, honey, nut, pungent	Oven dried and blanched *Acheta domesticus* and *Gryllus assimilis*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates. Protein isolates from *Protaetia brevitarsis*	(Grossmann *et al*., 2021; Khatun *et al*., 2021; Lee *et al*., 2021)
Octanal	Citrus, grassy, green, fat, soap, lemon, mushroom, mouldy	Freeze dried Australian green ants. *Lethocerus indicus*. raw, boiled and roasted *Ruspolia differens*. . *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Alagappan *et al*., 2021; Grossmann *et al*., 2021; Mahattanatawee *et al*., 2018; Ssepuuya *et al*., 2020)
Nonanal	Citrus, fatty, green, aldehydic	Freeze-drying Australian green ants, freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis* raw, boiled and roasted *Ruspolia differens*. honey bee larvae and pupae powders. . *Allomyrina dichotoma*	(Alagappan *et al*., 2021; Haber et al., 2019a; Khatun *et al*., 2021; Kim *et al*., 2021; Ssepuuya *et al*., 2020)
(E,E)-2,4-Nonadienal	Fatty, cucumber, green, melon	*Lethocerus indicus*, frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2014, 2015; Mahattanatawee *et al*., 2018)
(E)-2-Nonenal	Metallic, fatty, hay-like, tallowy, cucumber-like	*Lethocerus indicus*, frozen fresh *Lethocerus indicus. Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)

Volatile Compounds	Sensory attribute	Edible insect	Reference
(Z)-2-Nonenal	Fatty, metallic, geranium, cucumber	*Lethocerus indicus*, frozen, fresh and salted boiled *Lethocerus indicus*	(Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
(E,E)-2,4-Decadienal	Fatty, cooked grain, deep fried	*Lethocerus indicus*, frozen, fresh and salted boiled *Lethocerus indicus*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
Decanal	Fresh, mint, citrusy	*Lethocerus indicus*, oven dried *Acheta domesticus* and freeze dried, oven dried and blanched *Gryllus assimilis*	(Khatun *et al*., 2021; Mahattanatawee *et al*., 2018)
(E)-4,5-Epoxy-(E)-2-decenal	Metallic, waxy	Frozen fresh and salted boiled *Lethocerus indicus*. *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015)
2-Butyl-2-octenal		Freeze dried *Acheta domesticus* and *Gryllus assimilis*, Vacuum dried *Tenebrio molitor* larvae	(Khatun *et al*., 2021; Kröncke *et al*., 2019)

Table 5. Most common volatile ketones and alcohols identified in diverse edible insects.

Volatile Compounds	Sensory attribute	Edible insect	Reference
Ketones			
Acetoin (3-Hydroxy-2-butanone)	Buttery	Raw and microwave dried locust and *Bombyx mori*. *Allomyrina dichotoma. Alphitobius diaperinus, Acheta domesticus* and *Blaptica dubia* oils.	(Kim *et al*., 2021; Mishyna et al., 2020; Tzompa-Sosa *et al*., 2019)
2-Butanone	Ethereal, fruity, camphoreous	Raw, freeze and oven dried locust and microwave dried *Bombyx mori*, rack oven dried and vacuum dried *Tenebrio molitor* larvae, . *Allomyrina dichotoma*	(Kim *et al*., 2021; Kröncke *et al*., 2019; Mishyna *et al*., 2020)
Diacetyl	Buttery	Honey bee larvae powders. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Haber et al., 2019a)
2,3-Pentanedione	Buttery	*Allomyrina dichotoma*. *Acheta domesticus* and protein and hydrolysates	(Grossmann *et al*., 2021; Kim *et al*., 2021)
2-Pentanone	Fruity,	*Allomyrina dichotoma*.	(Kim *et al*., 2021; Lee *et al*., 2021)
2-Heptanone	Cheesy, fruity, spicy, sweet	Raw and freeze, oven and microwave dried locust, freeze dried *Acheta domesticus* and *Gryllus assimilis*, rack oven dried and vacuum dried *Tenebrio molitor* larvae, raw, boiled and roasted *Ruspolia differens*. Honey bee pupae powders. *Acheta domesticus* oil.	(Haber et al., 2019a; Khatun *et al*., 2021; Kröncke *et al*., 2019; Mishyna et al., 2020; Ssepuuya *et al*., 2020; Tzompa-Sosa *et al*., 2019)
Acetophenone	Floral, almond, animal, flower, must, plastic	*Allomyrina dichotoma*. Protein isolates from *Protaetia brevitarsis*	(Kim *et al*., 2021; Lee *et al*., 2021)
5-Methyl-3-hepten-2-one	Green	Roasted *Tenebrio molitor* and *Zophobas morio*, freeze dried *Acheta domesticus* and *Gryllus assimilis*	(Khatun *et al*., 2021; Żołnierczyk & Szumny, 2021)
(E,E)-3,5-Octadien-2-one	Fruity, green, grassy	Freeze dried *Acheta domesticus* and *Gryllus assimilis.* Raw and freeze dried locust and oven dried *Bombyx mori. Patanga succincta L powder*	(Indriani *et al*., 2021; Khatun *et al*., 2021; Mishyna *et al*., 2020)
1-Octen-3-one	Mushroom, metallic	*Lethocerus indicus.* Frozen fresh and salted boiled *Lethocerus indicus. Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
2-Nonanone	Fragrant, fruit, green, hot milk, cheese, coconut	Roasted *Tenebrio molitor* and *Zophobas morio*. boiled and roasted *Ruspolia differens* and *Allomyrina dichotoma. Acheta domesticus* oil	(Kim *et al*., 2021; Ssepuuya *et al*., 2020; Tzompa-Sosa *et al*., 2019; Żołnierczyk & Szumny, 2021)
2-Decanone	Fruity, floral, fatty	Raw, boiled and roasted *Ruspolia differens. Allomyrina dichotoma*. Protein isolates from *Protaetia brevitarsis*	(Kim *et al*., 2021; Lee *et al*., 2021; Ssepuuya *et al*., 2020)
1-Undecen-3-one	Mushroom	Frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*	(Kiatbenjakul *et al*., 2014, 2015)
β-Ionone	Raspberry, floral, violet-like	*Lethocerus indicus. Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Mahattanatawee *et al*., 2018)
Alcohols			
2,3-Butanediol	Creamy	*Allomyrina dichotoma*. *Schistocerca gregaria* and *Ruspolia differens* oils	(Cheseto *et al*., 2020; Kim *et al*., 2021)
2-Methyl-1-propanol (Isobutanol)	Ethereal, sweet	*Allomyrina dichotoma*. *Alphitobius diaperinus, Blaptica dubia, Acheta domesticus* and *Tenebrio molitor* oils	(Kim *et al*., 2021; Tzompa-Sosa *et al*., 2019)
3-Methyl-1-butanol	Fermented, whisky, malty	Raw and microwave dried locust. *Allomyrina dichotoma*. *Ruspolia differens* and *Acheta domesticus* oils.	(Cheseto *et al*., 2020; Kim *et al*., 2021; Mishyna *et al*., 2020; Tzompa-Sosa *et al*., 2019)
1-Pentanol	Fermented, oily, sweet, vinegar	Raw and microwave dried locust. *Ruspolia differens, Blaptica dubia* and *Acheta domesticus* oils	(Cheseto *et al*., 2020; Mishyna *et al*., 2020; Tzompa-Sosa *et al*., 2019)
1-hexanol	Herbal, flower, fruit, green, wood	Freeze dried Australian green ants. Protein isolates from *Protaetia brevitarsis*. *Alphitobius diaperinus* oil	(Alagappan *et al*., 2021; Kim *et al*., 2021; Lee *et al*., 2021; Tzompa-Sosa *et al*., 2019)

Volatile Compounds	Sensory attribute	Edible insect	Reference
(E)-2-Hexenol	Fruity, orange-like, Green, leafy	Frozen fresh and salted boiled *Lethocerus indicus*. *Lethocerus indicus*	(Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
2-Ethyl-1-hexanol	Citrus, green, flowery	Raw and freeze, oven and microwave dried *Bombyx mori*. *Harmonia axyridis* beetles. *Allomyrina dichotoma*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kim *et al*., 2021; Mishyna *et al*., 2020)
3,5-Octadien-2-ol		Freeze dried, *Acheta domesticus* and freeze dried and oven dried *Gryllus assimilis*, Raw and freeze dried locust	(Khatun *et al*., 2021; Mishyna *et al*., 2020)
1-Octanol	Fatty, waxy	*Lethocerus indicus*	(Kim *et al*., 2021; Mahattanatawee *et al*., 2018)
1-Octen-3-ol	Earthy, fishy, fat, mould, mushroom	Freeze dried and blanched *Acheta domesticus* and freeze dried, oven dried and blanched *Gryllus assimilis Allomyrina dichotoma.* Protein isolates from *Protaetia brevitarsis*. *Acheta domesticus*, *Schistocerca gregaria* and *Ruspolia differens* oils	(Cheseto *et al*., 2020; Khatun *et al*., 2021; Kim *et al*., 2021; Lee *et al*., 2021; Tzompa-Sosa *et al*., 2019)

Table 6. Most common volatile carboxylic acids and esters reported in edible insects.

Volatile Compounds	Sensory attribute	Edible insect	Reference
Carboxylic Acids			
Acetic acid	Acidic, sharp, pungent, vinegar, sour	Raw and freeze, oven and microwave dried locust and *Bombyx mori*. *Lethocerus indicus*. *Harmonia axyridis* beetles. *Tenebrio molitor*, Alphitobius diaperinus and Acheta domesticus oils.	(Mahattanatawee *et al*., 2018; Mishyna *et al*., 2020; Tzompa-Sosa *et al*., 2019)
Butanoic acid	Cheesy, acetic, faecal, fatty, rancid, sweaty, vomitus	Oven dried locust and microwave dried *Bombyx mori*, *Lethocerus indicus*, Frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*. Oven dried *Musca domestica*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates. *Acheta domesticus* and *Blaptica dubia* oils	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2014, 2015; Mahattanatawee *et al*., 2018; Mishyna *et al*., 2020; Sánchez *et al*., 2021; Tzompa-Sosa *et al*., 2019)
2-Methylpropanoic acid	Acidic, sour, cheesy, fatty	Oven and microwave dried locust, freeze dried *Tenebrio molitor* larvae. *Tenebrio molitor* protein and hydrolysates. *Blaptica dubia* oil.	(Grossmann *et al*., 2021; Kröncke *et al*., 2019; Mishyna *et al*., 2020; Tzompa-Sosa *et al*., 2019)
2-Methylbutanoic acid	Faecal, sweaty	Frozen fresh and salted boiled *Lethocerus indicus*, oven dried *Acheta domesticus* and *Gryllus assimilis*, freeze dried *Tenebrio molitor* larvae. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Khatun *et al*., 2021; Kiatbenjakul *et al*., 2015; Kröncke *et al*., 2019)
3-Methylbutanoic acid (Isovaleric acid)	Cheesy, sour, sweaty, faecal, feet	Oven dried locust, Frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*, oven dried *Acheta domesticus* and *Gryllus assimilis. Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates. Freeze dried *Tenebrio molitor* larvae. *Harmonia axyridis* beetles. *Blaptica dubia* oil	(Grossmann *et al*., 2021; Khatun *et al*., 2021; Kiatbenjakul *et al*., 2014; 2015; Kröncke *et al*., 2019; Mishyna *et al*., 2020; Tzompa-Sosa *et al*., 2019)
Hexanoic acid	Sweaty, cheesy, body odour	*Lethocerus indicus*, Frozen fresh and salted boiled *Lethocerus indicus*, freeze dried *Acheta domesticus* and *Gryllus assimilis*, vacuum dried *Tenebrio molitor* larvae. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Alagappan *et al*., 2021; Grossmann *et al*., 2021; Khatun *et al*., 2021; Kiatbenjakul *et al*., 2015; Kröncke *et al*., 2019; Mahattanatawee *et al*., 2018)
(E)-2-Hexenoic acid	Sweaty, body odour, fruity	Frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*	(Kiatbenjakul *et al*., 2014, 2015)
Dodecanoic acid		Oven dried and blanched *Acheta domesticus* and freeze dried, oven dried and blanched *Gryllus assimilis*. *Protaetia brevitarsis* powder	(Khatun *et al*., 2021; Yeo *et al*., 2013)
Tetradecanoic acid		Oven dried and blanched *Acheta domesticus* and freeze dried, oven dried and blanched *Gryllus assimilis*. *Protaetia.* Sun dried *Polyrhachis vicina* Roger. *Protaetia brevitarsis* powder	(Khatun *et al*., 2021; Li *et al*., 2009; Yeo *et al*., 2013)
n-Hexadecanoic acid		*Protaetia brevitarsis* powder, *Polyrhachis vicina* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Shen *et al*., 2006; Yeo *et al*., 2013)
9-Hexadecenoic acid		*Protaetia brevitarsis* powder. Sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Yeo *et al*., 2013)
[E]-9-Octadecenoic acid		*Polyrhachis vicina* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Shen *et al*., 2006)
Esters			
Ethyl acetate	Sweet, weedy, green, fruity, ethereal	Oven dried locust and raw, freeze dried, oven dried and microwave dried *Bombyx mori*. *Allomyrina dichotoma*. Honey bee pupae powders	(Haber et al., 2019a; Kim *et al*., 2021; Mishyna *et al*., 2020)
Methyl hexanoate		Freeze dried and oven dried *Acheta domesticus* and *Gryllus assimilis. Patanga succincta* L defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
(E)-2-Hexenyl acetate	Sweet herbaceous, fruity, banana peel, unripe	*Lethocerus indicus*, frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*	(Kiatbenjakul *et al*., 2014, 2015; Mahattanatawee *et al*., 2018)
(E)-2-Heptenyl acetate	Green, fatty, fruity	*Lethocerus indicus*, frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*	(Kiatbenjakul *et al*., 2014, 2015; Mahattanatawee *et al*., 2018)

Volatile Compounds	**Sensory attribute**	**Edible insect**	**Reference**
(E)-2-Hexenyl butanoate	Floral, fruity, cheesy, banana peel	*Lethocerus indicus*, frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus*	(Kiatbenjakul *et al*., 2014, 2015; Mahattanatawee *et al*., 2018)
Methyl dodecanoate		Freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis. Patanga succincta* L defatted and non-defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
Methyl tetradecanoate		Freeze dried and oven dried *Acheta domesticus* and freeze dried, oven dried and blanched and *Gryllus assimilis. Patanga succincta* L defatted and non-defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
Methyl hexadecanoate		Freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis. Patanga succincta* L defatted and non-defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
Ethyl hexadecanoate		*Protaetia brevitarsis* powder, *Polyrhachis vicina* powder	(Shen *et al*., 2006; Yeo *et al*., 2013)
Methyl octadeca-9,12-dienoate		Freeze dried and oven dried *Acheta domesticus* and freeze dried, oven dried and blanched *Gryllus assimilis. Patanga succincta* L defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
Methyl octadecanoate		Freeze dried, oven dried and blanched *Acheta domesticus* and *Gryllus assimilis*. *Patanga succincta* L defatted powder	(Indriani *et al*., 2021; Khatun *et al*., 2021)
Ethyl oleate		*Protaetia brevitarsis* powder, *Polyrhachis vicina* powder	(Shen *et al*., 2006; Yeo *et al*., 2013)

Table 3. Settings of different GC/MS-based methods used for edible insect volatile analysis

Edible insect	Sample form	Extraction	Incubation time (min)	Temperature Incubation/ extraction (°C)	Extraction time (min)	Fibre	Column				Mass range (m/z)	Reference
							Type	Length (m)	Internal diameter (mm)	Film thickness (µm)		
Lethocerus indicus	Aroma extract dilutions	Solvent extraction	N/A	N/A	N/A	N/A	SAC-5	30	0.25	0.25	35-300	(Kiatbenjakul et al., 2014, 2015)
Schistocerca gregaria and *Ruspolia differens*	Oil	Extraction using Super-Q traps	N/A	N/A	N/A	N/A	HP-5ms	30	0.25	0.25	40-550	(Cheseto et al., 2020)
Polyrhachis vicina Roger	Fresh and powder	Extraction by hexane	N/A	N/A	N/A	N/A	DB-5ms	30	0.25	0.25	40-350	(Li et al., 2009)
Ruspolia differens	Fresh and cooked entire sample	SPME	10	45/45	20	CAR/PDMS	ZB-5	30	0.25	0.25	30-350	(Ssepuuya et al., 2020, 2021)
Tenebrio molitor and *Zophobas morio*	Powder	SPME	10	70/70	20	DVB/CAR/PDMS	ZB-5	30	0.25	0.25	30-350	(Khatun et al., 2021)
Tenebrio molitor Alphitobius diaperinus Acheta domesticus and *Blaptica dubia*	Oil	SPME	20	40	5	DVB/CAR/PDMS	Stabilwax-DA-Carbowax	30	0.32	1	33-250	(Tzompa-Sosa et al., 2019)
Apis mellifera	Powder	SPME	15	50/50	30	DVB/CAR/PDMS	DB-WAX	60	0.25	0.25	40-450	(Haber et al., 2019a)
Locusta migratoria manilensis Bombyx mori	Fresh and powder	SPME	60	25/25	30	DVB/CAR/PDMS	DB-WAX	60	0.25	0.5	33-500 (amu)	(Mishyna et al., 2020)
Patanga succincta L.	Defatted and non-defatted water dissolved powders	SPME	600	60	60	DVB/CAR/PDMS	HP-Innowax	30	0.25	0.25	25-500	(Indriani et al., 2021)
Cricket (*n.e.*)	powder	SPME	20	50/50	40	DVB/CAR/PDMS	DB-WAX	30	0.25	0.5	N/A	(Patrignani et al., 2020)
Oecophylla smaragdina	Powder	SPME	20	60/60	10	DVB/CAR/PDMS	DB-WAX	60	0.25	0.25	30-300	(Alagappan et al., 2021; Olarte Mantilla et al., 2020)

Edible insect	Sample form	Extraction	Incubation time (min)	Temperature Incubation/ extraction (°C)	Extraction time (min)	Fibre	Column				Mass range (m/z)	Reference
							Type	Length (m)	Internal diameter (mm)	Film thickness (μm)		
Tenebrio molitor	Dried sample	SPME	15	100/50	30	N/A	Rtx	60	0.25	1	N/A	(Kröncke et al., 2019)
Musca domestica	Micro encapsulated Powder	SPME	30	40/40	5	DVB/CAR/PDMS	Rxi--5	30	0.25	1	30-500	(Sánchez et al., 2021)
Tenebrio molitor and *Zophobas morio*	Entire	SPME	N/A	50	30	DVB/CAR/PDMS	ZB-5	30	0.25	0.25	-	(Żołnierczyk & Szumny, 2021)
Allomyrina dichotoma	Powder	SPME	20	70	30	DVB/CAR/PDMS	DB-WAX	60	0.25	0.25	35-500	(Kim et al., 2021)
Acheta domesticus and *Tenebrio molitor*	Powder	SPME	10	65/65	30	DVB/CAR/PDMS	DB-FFAP	30	0.32	0.25	33-300	(Grossmann et al., 2021)
Lethocerus indicus	In pieces	SPME	15	40	30	DVB/CAR/PDMS	DB-WAX	30	0.32	0.2	20-300	(Mahattanatawee et al., 2018)
Protaetia brevitarsis	Powder	SPME Arrow	15	40	60	DVB/CAR/PDMS	HP-5 ms	60	0.25	0.25	30-530	(Lee et al., 2021)
Protaetia brevitarsis	Power	SDE[2]	N/A	N/A	N/A	N/A	HP-5 ms	30	0.25	0.25	N/A	(Yeo et al., 2013)
Polyrhachis vicina	Powder	SFE[3]-CO_2	N/A	N/A	N/A	N/A	Silica column	30	0.25	0.25	10-55 units	(Shen et al., 2006)

[1] SPME=Solid phase microextraction; [2] SDE=Simultaneous distillation extraction; [3] SFE=Supercritical Fluid System Extraction;
N/A=Not Available; *n.e.*= species not specified

Table 7. Other volatile compounds reported in edible insects.

Volatile Compounds	Sensory attribute	Edible insect	Reference
Linear hydrocarbons			
Octane	Gasoline, alkane	Raw, freeze and microwave dried locust and microwave dried *Bombyx mori*. Honey bee larvae and pupae powders. *Allomyrina dichotoma*	(Haber et al., 2019a; Kim *et al*., 2021; Mishyna *et al*., 2020)
Decane	Odourless	Freeze dried Australian green ants. Honey bee larvae and pupae powders.	(Alagappan *et al*., 2021; Haber et al., 2019a)
Undecane	Odourless	Freeze and microwave dried locust and raw, freeze and microwave dried *Bombyx mori*. Freeze dried Australian green ants. Honey bee larvae and pupae powders. *Allomyrina dichotoma*. Fresh and sun dried *Polyrhachis vicina* Roger	(Alagappan *et al*., 2021; Haber et al., 2019a; Kim *et al*., 2021; Li *et al*., 2009; Mishyna *et al*., 2020)
Dodecane	Odourless	Freeze dried Australian green ants. Honey bee larvae and pupae powders. *Allomyrina dichotoma*	(Alagappan *et al*., 2021; Haber et al., 2019a; Kim *et al*., 2021)
Tridecane	Odourless	Freeze dried Australian green ants. Honey bee pupae powder. *Allomyrina dichotoma*. Oven dried *Musca domestica*. Fresh and sun dried *Polyrhachis vicina* Roger	(Alagappan *et al*., 2021; Haber et al., 2019a; Kim *et al*., 2021; Li *et al*., 2009; Sánchez *et al*., 2021)
Pentadecane	Waxy	*Allomyrina dichotoma*. Fresh and sun dried *Polyrhachis vicina* Roger	(Kim *et al*., 2021; Li *et al*., 2009)
Hexadecane	Odourless	Honey bee pupae powders. Oven dried *Musca domestica*. Fresh and sun dried *Polyrhachis vicina* Roger	(Haber et al., 2019a; Li *et al*., 2009; Sánchez *et al*., 2021)
Heptadecane		*Protaetia brevitarsis* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Yeo *et al*., 2013)
Eicosane	Odourless	*Protaetia brevitarsis* powder. Honey bee larvae powder. Fresh *Polyrhachis vicina* Roger	(Haber et al., 2019a; Li *et al*., 2009)
Heneicosane		*Protaetia brevitarsis* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Yeo *et al*., 2013)
Hexacosane		*Protaetia brevitarsis* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Yeo *et al*., 2013)
Heptacosane		*Protaetia brevitarsis* powder. Fresh and sun dried *Polyrhachis vicina* Roger	(Li *et al*., 2009; Yeo *et al*., 2013)
Aromatic and cyclic hydrocarbons			
Styrene	Gasoline, plastic, rubber, solvent	Protein isolates from *Protaetia brevitarsis*. *Schistocerca gregaria* and *Ruspolia differens* oils	(Cheseto *et al*., 2020; Lee *et al*., 2021)
p-Xylene	Cold meat fat, metal	Protein isolates from *Protaetia brevitarsis. Schistocerca gregaria oil*	(heseto *et al*., 2020; Lee *et al*., 2021)
Pyrazines			
2,3-Dimethyl-pyrazine	Nutty, cocoa, peanut	Microwave dried locust and *Bombyx mori*. *Allomyrina dichotoma*	(Kim *et al*., 2021; Mishyna *et al*., 2020)
2,5-Dimethylpyrazine	Cocoa, roast beef, roasted nut, burnt, Chocolate	Roasted *Tenebrio molitor* and *Zophobas morio*, oven dried *Acheta domesticus* and *Gryllus assimilis*, rack oven dried, freeze dried and vacuum dried *Tenebrio molitor* larvae, microwave dried locust and *Bombyx mori*. *Allomyrina dichotoma*. Oven dried *Musca domestica*	(Khatun *et al*., 2021; Kim *et al*., 2021; Kröncke *et al*., 2019; Mishyna *et al*., 2020; Sánchez *et al*., 2021; Żołnierczyk & Szumny, 2021)
Ethyl pyrazine	Nutty, peanut, butter, musty	Microwave dried locust and *Bombyx mori*. *Allomyrina dichotoma*	(Kim *et al*., 2021; Mishyna *et al*., 2020)
2-Ethyl-5-methylpyrazine	Fruit, green, coffee, beany, nutty	Roasted *Tenebrio molitor* and *Zophobas morio*, microwave dried locust and *Bombyx mori*	(Mishyna *et al*., 2020; Żołnierczyk & Szumny, 2021)
2-Ethyl-6-methylpyrazine	Roasted hazelnut, buckwheat tea, fruity, potato	Roasted *Tenebrio molitor* and *Zophobas morio*, microwave dried locust and *Bombyx mori*	(Mishyna *et al*., 2020; Żołnierczyk & Szumny, 2021)
2,3,5-Trimethylpyrazine	Cocoa, earth, must, potato, roast, nutty	Roasted *Tenebrio molitor* and *Zophobas morio. Allomyrina dichotoma*	(Kim *et al*., 2021; Żołnierczyk & Szumny, 2021)

Volatile Compounds	Sensory attribute	Edible insect	Reference
Tetramethylpyrazine	Earthy-like	Oven dried *Musca domestica*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Sánchez *et al*., 2021)
Other N-compounds			
2-Acetyl-1-pyrroline	Popcorn, roasty, sweet	Salted boiled *Lethocerus indicus*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015)
Indole	Barnyard, mothball, burnt, faecal	*Harmonia axyridis* beetles. *Allomyrina dichotoma*. *Acheta domesticus* hydrolysates	(Grossmann *et al*., 2021; Kim *et al*., 2021)
S- compounds			
Dimethyl sulphide	Sulphurous, onion, sweet	Freeze and microwave dried locust, honey bee pupae powders	(Haber et al., 2019a; Mishyna *et al*., 2020)
Methional	Cooked potato, soy, warm	*Lethocerus indicus*, salted boiled *Lethocerus indicus*. Protein isolates from *Protaetia brevitarsis*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Lee *et al*., 2021; Mahattanatawee *et al*., 2018)
2-Acetyl-2-thiazoline	Cooked jasmine rice, popcorn	*Lethocerus indicus*, salted boiled *Lethocerus indicus*. *Acheta domesticus* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
Phenols			
2-Methoxyphenol (Guaiacol)	Smoke, medicine, phenol	*Raw* and frozen fresh *Lethocerus indicus*. *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2015; Mahattanatawee *et al*., 2018)
4-Methylphenol (p-Cresol)	Animal, barmy, dung, stable, phenolic, faecal	Frozen fresh and salted boiled *Lethocerus indicus*, extract of scent glands of *Lethocerus indicus* *Allomyrina dichotoma*. *Acheta domesticus* and *Tenebrio molitor* protein and hydrolysates	(Grossmann *et al*., 2021; Kiatbenjakul *et al*., 2014, 2015; Kim *et al*., 2021)
Terpenes			
Limonene	Terpenic, pine, herbal, citrus, lemon, orange	Raw and freeze, oven and microwave dried locust and Freeze and microwave dried *Bombyx mori*. raw, boiled and roasted *Ruspolia differens*. *Allomyrina dichotoma*. *Ruspolia differens* oil	(Cheseto *et al*., 2020; Kim *et al*., 2021; Mishyna *et al*., 2020; Ssepuuya *et al*., 2020)
α-Pinene	Resin, minty, pine like	*Ruspolia differens* and *Acheta domesticus* oils	(Cheseto *et al*., 2020; Tzompa-Sosa *et al*., 2019)
γ-Terpinene	Citrus, mint, resin, lemon	Protein isolates from *Protaetia brevitarsis*. *Acheta domesticus* oil	(Lee *et al*., 2021; Tzompa-Sosa *et al*., 2019)
Furans			
Furfural (Furan-2-carbaldehyde)	Almond, baked potatoes, bread, burnt, spice, bready	Roasted *Tenebrio molitor* and *Zophobas morio. Allomyrina dichotoma*	(Kim *et al*., 2021; Żołnierczyk & Szumny, 2021)
Furfurol (2-Furanmethanol)	Bready, , alcoholic, musty	Microwave dried locust. *Allomyrina dichotoma*	(Kim *et al*., 2021; Mishyna *et al*., 2020)
2-Pentylfuran	Fruity, green, earthy, beany, buttery, fishy, grassy	Microwave dried locust, freeze dried and oven dried *Acheta domesticus* and *Gryllus assimilis*, vacuum dried *Tenebrio molitor* larvae. raw, boiled and roasted *Ruspolia differen. Allomyrina dichotoma*	(Khatun *et al*., 2021; Kim *et al*., 2021; Kröncke *et al*., 2019; Mishyna *et al*., 2020; Ssepuuya *et al*., 2020)

Declaration of interests

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

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