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REVIEW

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The gastronomic art of edible insects: cooking methods and food innovation

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Edible insects are considered a promising and valuable food source with high potential nutritional value and environmental benefits. Better inclusion of edible insects into the daily diet could reduce the environmental burden and address food insecurity. Nevertheless, consumers often lack adequate knowledge and familiarity with insects, leading to low acceptance and negative attitudes towards insects. Therefore, this review focuses on the nutritional value of edible insects, cooking methods, and current applications of edible insect-based foods, aiming to help consumers and the food industry learn and understand the utilisation knowledge of edible insects and better introduce them into dishes, diets, and food products, thereby improving the gastronomic experience and consumer acceptance. Overall, this review could provide useful information to support further innovation in the culinary use and gastronomic development of edible insects, as well as ways to promote the utilisation of edible insects in the daily diet.

Sustainability spotlight

Edible insects are considered a promising and valuable food source that has high potential to address food insecurity. However, consumers have low acceptance and negative attitudes toward edible insects due to a lack of knowledge of edible insects and their cooking methods, which leads to challenges in introducing them into daily diets. To this end, this review is expected to provide the knowledge and utilisation methods of edible insects and support the development of insect-based food products and promote inclusion of edible insects in daily diets, contributing to SDG 2 (zero hunger), SDG 12 (ensure sustainable consumption and production), and SDG 13 (climate action).

1 Introduction

The increasing world population is driving the search for novel food sources to meet the growing food demand.[1] The nutritional properties and environmental benefits of edible insects make them a promising and valuable food source and are seen as part of a global strategy to address food insecurity and reduce the environmental burden, contributing to the achievement of sustainable development goals (SDG), *i.e.* SDG 2 (zero hunger), SDG 12 (ensure sustainable consumption and production), and SDG 13 (climate action).[2,3]

Despite the advantages of edible insects as a promising food source, many consumers have low acceptance and negative attitudes toward insects because they are regarded as dirty, dangerous, and primitive food.[4,5] Besides that, consumers often lack adequate understanding of cooking methods and practical knowledge related to the use of edible insects, leading to challenges in incorporating them into daily dishes.[5,6] Subsequently, edible insects are still regarded as an unfamiliar food source which could cause fear and food neophobia.[7] These factors make the utilisation of edible insects as a food source in the daily diet still a significant challenge. In this context, providing and promoting the cooking knowledge of edible insects to consumers is a key to improving their acceptability and popularisation, helping to reduce neophobia towards edible insects.[8,9] Furthermore, cooking can contribute to the safety and sensory qualities of the final products, thereby improving the overall gastronomic experience for consumers and increasing the acceptance of insect products.[10–12] On the other hand, several studies have shown that the incorporation of edible insect flours into familiar food products is a useful strategy that could reduce food neophobia and increase consumer acceptance by making insects invisible.[13,14] Considering the nutritional value and environmental benefits of edible insects, the reformulation of food products with edible insects could potentially improve their nutritional quality and sustainability and offer opportunities to introduce edible insects into the daily diet.[15–18]

Therefore, this review focuses on the nutritional value of edible insects, cooking methods, and current applications of edible insect-based foods, aiming to help consumers and the food industry learn and understand the utilisation knowledge of edible insects and better introduce them into dishes, diets, and food products, thereby improving the gastronomic experience and consumer acceptability. Overall, this review could

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provide useful information to promote the utilisation of edible insects in the diet and food product development, thereby increasing familiarity and acceptance of edible insects.

2 Nutritional potential of edible insects

Edible insects contain diverse essential nutrients for human growth and health, such as protein, oil, fibre, minerals, vitamins, and bioactive compounds, and have been considered a sustainable and highly nutritious food source.[19–21] Notably, the nutritional composition of edible insects varies depending on multiple factors, such as species, developmental stages, rearing conditions, gender, and origin.[22–25]

The protein content (based on dry matter) of edible insects has been reported to range from 32.9% to 76.0% w/w.[26–29] In addition, Köhler *et al.*[30] analysed the amino acid profile of four types of edible insects commonly consumed in Thailand, including Bombay locust (*Patanga succincta* L.), scarab beetle (*Holotrichia* sp.), house cricket (*Acheta domesticus*), and mulberry silkworm (*Bombyx mori* L.). The results showed that all reported edible insects contained 9 essential amino acids, with leucine and lysine being the most abundant. In terms of oil content, the oil content of edible insects ranges from 8.0% to 50.9% w/w.[31,32] Additionally, the oil fraction of edible insects contains high levels of unsaturated fatty acids, such as oleic acid (C18:1), linoleic acid (C18:2), and arachidonic acid (C20:4), which are important for human health and growth.[33–35] Perez-Santaescolastica *et al.*[36] analysed the fatty acid profile of 7 edible insects, namely house cricket (*Acheta domesticus*), lesser mealworm (*Alphitobius diaperinus*), orange-spotted roach (*Blaptica dubia*), honeycomb moth (*Galleria mellonella*), migratory locust (*Locusta migratoria*), mealworm (*Tenebrio molitor*), and kingworm (*Zophobas morio*). The results showed that all analysed edible insects contained high levels of oleic acid (C18:1, 23.30–54.26%) and linoleic acid (C18:2, 15.66–36.67%).

In addition to being rich sources of protein and oil, edible insects, such as mealworm and cricket, contain significant amounts of essential minerals, including potassium (287–1540 mg/100 g), calcium (176–265 mg/100 g), iron (4.2–6.4 mg/100 g), and zinc (10.0–26.3 mg/100 g).[37,38] Besides that, edible insects contain abundant bioactive compounds and vitamins. Jiang *et al.*[39] evaluated bioactive compounds in 6 types of edible insect oils, including *Tenebrio molitor*, *Protaetia brevitarsis*, *Teleogryllus mitratus*, *Locusta migratoria manilensis*, *Cryptotympana atrata*, and *Clanis bilineata tingtauica*. The results showed that all analysed edible insect oils contained high levels of squalene (25.10–1344 mg kg^{-1} of oil) and tocopherols (2.46–160.24 mg kg^{-1} of oil), with *Cryptotympana atrata* having the highest content of squalene and tocopherols. In addition, Gangopadhyay *et al.*[40] evaluated the vitamin content of eri silkworm pupae (*Samia ricini*) and found that they contained vitamin A (0.58–0.67 mg/100 g), vitamin E (36.88–41.35 mg/100 g), vitamin C (4.97–5.24 mg/100 g), vitamin B_1 (1.32–1.47 mg/100 g), vitamin B_2 (3.55–3.84 mg/100 g), vitamin B_3 (13.86–16.73 mg/100 g), vitamin B_6 (0.37–0.53 mg/100 g), and vitamin B_9 (1.95–2.33 mg/100 g). Schmidt *et al.*[41] quantitatively determined the vitamin B_{12} content in mealworm (*Tenebrio molitor*), grasshopper (*Locusta migratoria*), cricket (*Gryllus assimilis*), and cockroach (*Shelfordella lateralis*) using ultra-high performance liquid chromatography (UHPLC), and the contents were 1.08 (μg/100 g), 0.84 (μg/100 g), 2.88 (μg/100 g), and 13.21 (μg/100 g), respectively.

3 Environmental benefits

Edible insects are considered a sustainable and eco-friendly food source. Edible insects have many environmental benefits compared to traditional livestock, including less water, land, and feed use, and lower greenhouse gas (GHG) emissions.[19,42,43] It has been reported that the GHG emissions of mealworm with virgin feed (14.94 kg CO_2eq per kg protein) were significantly lower than those of beef (114.77 kg CO_2eq per kg protein).[43] Additionally, Oonincx & de Boer[42] stated that the production of mealworm only requires 10% of the land used for the production of beef. On the other hand, it has been reported that various agricultural by-products (*e.g.* carrot pomace and orange peel) can be used as feed for edible insect rearing, thereby contributing to a circular economy and sustainable food system.[44,45] Overall, using insects as food would be a promising strategy to reduce environmental burden and ensure food system sustainability.

4 Cooking methods of edible insects

Edible insects can be directly consumed raw and/or after cooking. In some regions with traditionally entomophagous practices, insects such as cicada and larvae and pupae of honeybee, can be consumed raw.[46,47] Notably, although insects are reportedly consumed raw, cooking is generally recommended to enhance safety, nutrient digestibility, and sensory quality of final products.[48,49] After cooking, the cooked insects can be consumed and/or added as part of innovative dishes.[50] Therefore, this section summarises the preparation and cooking methods of edible insects to better understand the utilisation methods of edible insects as food in order to facilitate introduction of insects into dishes and daily diets.

4.1 Preparation stage

After collection, insects are typically subjected to preliminary processing (preparation stage) to improve product quality before cooking, which varies depending on the species and their different developmental stages (*e.g.* eggs, larvae, pupae, and adults).[51] In general, larvae and adults of insects are preliminarily processed by removing the gut, wings, legs, and head. Table 1 summarises the preparation methods for some edible insects.

Generally, the first step is fasting for at least 24 h to reduce undigested residual food in the insect gut and the insect microbial loads.[22,52,53] Mancini *et al.*[54] evaluated the effect of fasting on the reduction of *L. monocytogenes* loads in mealworm and found that fasting was effective in reducing *Listeria*

Table 1 Preparation methods of edible insects

Insect	Preparation step	References
Rhinoceros beetle – larvae	Removal of the gut	12
Mopane worm – larvae	Removal of the hair and gut	47
Dragonfly – adult	Removal of the wings	46
Mantis – adult	Removal of the head, legs, and digestive tract	46,87
Cybister – adult	Removal of the wings	46
Grasshopper – adult	Removal of the wings and gut	47
Locust – adult	Removal of the wings, legs, and gut	47,88
Scarlet skimmer – larvae and adult	Removal of the wings	87
Giant water bug – adult	Removal of the wings	89

monocytogenes load. In addition, Melgar-Lalanne *et al.*[55] stated that insects are fasted for 1 to 3 days in order to eliminate bitter taste.

Hlongwane *et al.*[47] collected the traditional preparation knowledge of insects in South Africa (Limpopo and KwaZulu-Natal) and stated that larvae of the mopane worm (*Imbrasia belina*) were degutted and washed before cooking. In addition, stink bugs (*Encosternum delegorguei*) are consumed in South Africa following removing the head and scent glands.[56] Additionally, the larvae of the palm weevil (*Rhyncophorus phoenicis*) are prepared by removing the gut during the preparation stage.[57] Furthermore, the adult stages of cricket and grasshopper are reported to remove their wings, spiny legs, gut, and head during the preparation stage.[47,58,59] It is worth noting that the gut of insects contains various microbials and their wings and spines could be sharp, therefore, the use of gloves during the preparation procedure is recommended to protect hands and improve hygiene.[60]

4.2 Cooking stage

In the cooking stage, insects can be cooked using various methods, including boiling, roasting, grilling, smoking, oven drying, microwave heating, steaming, stir frying, deep frying, vacuum cooking, and fermentation.[12,49,61,62] Table 2 summarises some examples of domestic cooking methods and conditions for edible insects.

It has been reported that the edible caterpillar (*Imbrasia epimethea*) from northern Angola was consumed after boiling (30 min) and drying.[63] Ants are mainly consumed after roasting or frying, while wasps are consumed after roasting; in addition, palm weevil larvae are often pan-fried without oil, since they release their own oil during the frying process.[64] During stir frying, vegetables, spices, and sauce can be used as ingredients with insects; for example, silkworm pupae are stir fried with hot peppers in China.[65] In addition, *Udonga montana* has been reported to be boiled and further smoked to maintain its crispy texture.[46] Notably, roasting, grilling, and frying are the most

Table 2 Cooking methods and conditions of edible insects

Cooking method	Example of insect	Example of cooking conditions	References
Boiling	House cricket (*Acheta domesticus*)	The insects are boiled in boiling water (100 °C) for 15 min, with or without salt and or spices	49
Oven drying	House cricket (*Acheta domesticus*)	The insects are placed in a preheated oven at 110 °C for 30 min	49
Grilling	The African palm weevil (*Rhynchophorus phoenicis*)	The insects are pinned onto wooden sticks and grilled on charcoal flames for 10 min	61
Roasting	Long-horned grasshopper (*Ruspolia differens*)	The insects are placed on a plate without oil and roasted in an oven at 165 °C for 45 min	90
Smoking	The African palm weevil (*Rhynchophorus phoenicis*)	The insects are spread on a rack and smoked for 6 h in a smoking chamber using wood and soot	61
Steaming	House cricket (*Acheta domesticus*)	The insects are placed in a steamer for 5 min	91
Microwave heating	Mealworm (*Tenebrio molitor*)	The insects are placed in a bowl and heated in a microwave at 850 W for 10 min	92
Stir-frying	Mealworm (*Tenebrio molitor*)	The insects are stir fried in a preheated pan (175 °C) with vegetable oil for 4 min; 6.25 mL of oil/100 g of insects	93
Deep frying	Rhinoceros beetle (*Oryctes* spp)	The insects are fried in vegetable oil at 180 °C for 7 min; 120 g of insects in 200 mL of oil	12
Vacuum cooking	Mealworm (*Tenebrio molitor*)	The insects are vacuum-packed in a plastic bag and then immersed them in a thermostatically controlled water bath at 74 °C for 60 min	62
Fermentation	Mealworm (*Tenebrio molitor*)	The insects are mixed with steamed millet, salt, and malt power at a ratio of 80 : 20 : 5 : 1 (w/w/w/w) in an autoclaved jar and then fermented for 30 days at 15 °C	72

popular and attractive cooking methods.[64] Bisconsin-Júnior *et al.*[66] surveyed 780 participants in Brazil on their preferred method of eating insects and found that frying and roasting were the most preferred cooking methods. Besides, Caparros Megido *et al.*[67] reported that consumers showed a stronger preference for insects with a crispy texture (*e.g.* roasted and fried) compared to those insects with a juicy texture (*e.g.* boiled). Nevertheless, Klunder *et al.*[68] stated that roasting alone could not fully kill Enterobacteriaceae from the insects' intestines, while boiling was effective in fully killing them. Therefore, boiling can be combined with other cooking methods to improve food safety for insect cooking. For instance, the insects can be boiled and subsequently roasted to ensure safety and improve sensory qualities. It is important to note that the temperature and processing time vary depending on the insect species, developmental stages, and microbial target.[12,69] Besides, heterocyclic amines (HAAs), thermal processing contaminants, are carcinogenic and mutagenic chemicals formed from cooking high protein food products (*e.g.* meat and fish).[70,71] Considering the high protein content in edible insects, the cooking temperature and time should be considered during thermal cooking (*e.g.* roasting and grilling). Therefore, further studies are needed to explore and evaluate optimised cooking conditions for each cooking method to maintain safety, sensory quality, and the nutritional value of edible insects; in addition, the combination of cooking methods can also be investigated in further studies to improve the final product quality.

Besides, Kim *et al.*[72] reported a fermentation method for mealworm. The mealworm is washed using 2% saline solution and mixed with steamed millet, salt, and malt powder for 30 days at 15 °C.

5 Insect-based foods

Edible insects have been used as ingredients in food product development to enrich the nutritional profile of the final products, such as protein, fibre, and minerals.[15,16,73] In general, insect flour/powder is the main form used in food product development in order to hide them in the products and make them imperceptible to consumers, since most consumers are averse to products made with insects, and insects are uncommon ingredients in many countries and may cause food neophobia.[9,74] Therefore, hiding the distinctive insect appearance and including them in familiar food formulations (*e.g.*, bread, pasta, and sausage) are promising approaches to overcome food neophobia. Edible insects have been explored and used in several food products, as shown in Table 3.

In cereal products, bread, pasta, and sweet bakery products are popular and widely consumed staple and snack foods globally.[75,76] The global bakery products' market size was 495.6 billion USD in 2023 and is expected to reach 714.1 billion USD by 2030.[77] The use of insect flour in these products not only can improve the nutritional quality of the final product but also open up new possibilities for inclusion of insects into daily diets.[78] As shown in Table 3, edible insects are commonly used as wheat flour substitution in product development. For example, Gantner *et al.*[15] made bread using mealworm powder (up to 15% replacing level). The results showed that mealworm powder addition increased the bread nutritional value in terms of protein and oil. In addition, pasta is one of the popular staple foods in many countries, and the production is estimated at 14.3 million tons in the world.[79] Biró *et al.*[80] used silkworm powder as buckwheat flour substitution (5% and 10% levels) in pasta development. The results showed that 10% silkworm pasta had the highest overall liking score. It is important to note that the addition of insects may alter colour parameters and flavour of final products, depending on the insects used and addition level. In the study by Çabuk,[81] grasshopper powder addition in muffins generated strong unpleasant smell. In addition, Kowalski *et al.*[82] stated that sponge cakes made with insect flour had higher bitterness compared to the control sponge cakes. In the sensory evaluation, the reformulated sponge cakes had lower acceptability than the control. Taken together, more studies are needed to reduce or eliminate the off flavours to provide an attractive and high quality product for consumers, which can improve consumer acceptability for edible insect products.

In addition to the above products, insect flour has been used as a meat replacer in the development of sustainable meat products, including sausages, meat sauces, patties, meat emulsions, and meat spreads (Table 3). Meat is an excellent source of protein in the human daily diet. However, the production and consumption of animal-based meat products have adverse effects on the environment.[83] Therefore, utilisation and incorporation of edible insects as a meat replacer in meat product development could provide significant potential for

Table 3 Examples of applications of some edible insects in food development

Insect	Product	Function	Usage level	References
Mealworm (*Tenebrio molitor*)	Bread	Wheat flour substitution	5%, 10%, and 15%	15
House cricket (*Acheta domesticus*)	Pasta	Wheat flour substitution	5%	94
Buffalo worm (*Alphitobius diaperinus*)	Pancake	Wheat flour substitution	10%, 20%, and 30%	95
Kingworm (*Zophobas atratus*)	Biscuit	Wheat flour substitution	10%, 20%, and 30%	96
Grasshopper (*Locusta migratoria*)	Muffin	Wheat flour substitution	15%	81
House cricket (*Acheta domesticus*)	Meat patty	Beef substitution	5%, 7.5%, and 10%	85
Mealworm (*Tenebrio molitor*)	Sausage	Pork substitution	5%, 10%, and 15%	17
Mealworm (*Tenebrio molitor*)	Meat sauce	Meat substitution	50% and 100%	97
House cricket (*Acheta domesticus*)	Meat emulsion	Meat substitution	5% and 10%	98
Silkworm (*Bombyx mori*)	Meat spread	Chicken substitution	25%, 50%, and 75%	73

environmental sustainability.[84] Pasqualin Cavalheiro *et al.*[85] demonstrated that using house cricket flour as a beef replacer (5%, 7.5%, and 10%) in beef patties increased protein content and decreased cooking loss. In addition, Hospital *et al.*[17] used mealworm as the pork replacer in sausage formulation and found that the protein content of sausages increased with increasing mealworm flour addition. In sensory analysis, the reformulated sausages containing 10% mealworm showed a significant difference in all sensory parameters (*e.g.* colour, texture, odour, and taste) compared to the control sausages. Furthermore, Choi *et al.*[86] used 4 types of edible insect powders in pork patties and found that the pork patties containing edible insects had lower colour, flavour, umami, and juiciness scores than that of the control. Although the incorporation of edible insects into meat products improves the nutritional value, the sensory quality of reformulated products could be adversely affected. Therefore, more studies are needed to improve sensory quality. For example, other ingredients (*i.e.*, spices) could be combined with edible insects in meat product development to reduce and/or eliminate the influence of edible insects in the formulation.

6 Conclusions

Edible insects are a promising and valuable source of protein, oil, minerals, and bioactive compounds. The utilisation of edible insects in daily diets and food development could contribute to addressing food insecurity and building a sustainable food system. However, despite the many benefits of insects as food, negative consumer attitudes toward insects make it difficult for them to be introduced into the daily diet. A lack of knowledge and cooking methods have been identified as important factors influencing consumer attitudes towards insects as food. Therefore, providing consumers with the benefits and utilisation knowledge of insects and developing a variety of high quality insect-based food products could contribute to change their attitudes and improve the acceptability of insects as food, thereby promoting the utilisation of insects in daily diets.

Data availability

No primary research results, software, or code were included, and no new data were generated or analyzed as part of this review.

Author contributions

Guoqiang Zhang: conceptualization, investigation, visualization, writing – original draft, writing – review & editing. Shaopu Liu: writing – review & editing. Feiyu An: writing – review & editing. Rina Wu: writing – review & editing.

Conflicts of interest

The authors declare that they have no competing interests.

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