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Insect-based protein sources and their potential for human consumption: Nutritional composition and processing

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Implications

- Edible insects are, in general, rich in protein, fat, and energy and can be a significant source of vitamins and minerals.
- Insects are a sustainable alternative protein source in food and feed.
- Edible insects can contribute to food and feed security.
- The development of safe rearing and effective processing methods are mandatory for a utilization of insects in food and feed.

Key words: alternative protein source, entomophagy, food application, food security, functional properties

Introduction

The consumption of insects, also called entomophagy, is traditionally practiced by more than two billion people worldwide, mostly in Asia, Africa, and South America. Out of the more than 1,900 eaten species described in scientific literature, 31% are beetles (Coleoptera), 18% are caterpillars of butterflies and moths (Lepidoptera), 14% are bees, wasps, and ants (Hymenoptera), and 13% are locusts, grasshoppers, and crickets (Orthoptera) (van Huis et al., 2013).

Several beneficial aspects support an increased utilization of insects as a sustainable animal protein source. Compared with conventional livestock, insects have low space requirements, a high fecundity, and some species are multivoltine, which means that they undergo more than one life cycle per year. Insects emit less greenhouse gases and ammonia than pigs and cattle (Oonincx et al., 2010) and have a high feed conversion efficiency. For example, crickets only require 2 kg of feed to gain 1 kg body weight (van Huis et al., 2013). In addition, omnivorous insects can be reared on organic waste and contribute to their valorization into biomass. But most importantly, insects have the potential to contribute to protein, food, and feed security.

To date, commercially reared insects for human consumption include the house cricket, the palm weevil, the giant water bug, and water beetles (van Huis, 2013). Black soldier fly, the common housefly, and the yellow mealworm have been identified in a feasibility study on inclusion of insects in pig and poultry diets as the most promising species for mass-rearing on an industrial scale in the Western world (Veldkamp et al., 2012). Nevertheless, the majority of the insects consumed are still gathered in the wild (Government of Laos, 2010), and information on their nutrient composition is scarce. The present article presents an overview of the nutritive value of selected insect species and orders to illustrate the potential of insects as a source of essential nutrients in human diet. In addition, the importance of the development of processing of food insects and their products on an industrial scale and their potential application in food, for example, as protein source or texturizing agent is discussed.

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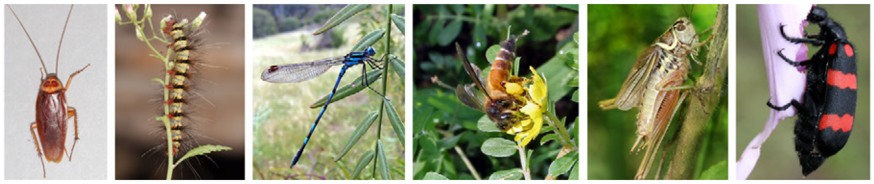
Nutrient Content of Edible Insects

Extensive research on the nutritional composition of edible insects is still required. Numerous scientific publications have reported on nutrient composition of different species; however, the published data vary tremendously, which is presumably mostly due to the methods of analyses as well as to differences among diets and origins of the studied insects. A compilation of 236 nutrient compositions of edible insects published to date showed that the main components of insects are protein and fat, followed by fiber, nitrogen-free extract, a value representing carbohydrates other than fiber, and ash (Rumpold and Schlüter, 2013). Table 1 summarizes average nutrient contents of different insect orders.

The main components of insects, protein and fat, are discussed in more details below. Fiber contents range from 5.1% for termites (Isoptera) to 13.6% for true bugs (Hemiptera). This includes chitin, a N-acetylglucosamine present in the exoskeleton of insects. On a dry matter basis, the range of chitin content of commercially reared insects extends from 11.6 to 137.2 mg/kg (Finke, 2007). Nitrogen-free extract content varies from 4.6% for dragonflies (Odonata) to 22.8% for termites (Isoptera), and the ash content varies between 2.9% for cockroaches (Blattodea) and 10.3% for flies (Diptera) (Rumpold and Schlüter, 2013). Energy content of edible insects ranges from 426.3 kcal/100 g for grasshopper, locusts, and crickets (Orthoptera) to 508.9 kcal/100 g for caterpillars (Lepidoptera) and is generally subject to large variations analogous to those of the nutrient components (Table 1). Out of the 113 energy content values reported in the literature, 90 are above 400 kcal/100 g and 44 above 500 kcal/100 g, with a value as high as 776.9 kcal/100 g reported for the caterpillar *Phasus triangularis* (Ramos-Elorduy et al., 1998).

Proteins

The protein content of edible insects on a dry matter basis ranges from 35.3% for termites (Isoptera) to 61.3% for crickets, grasshoppers, and locusts (Orthoptera) as shown in Table 1. Globally, edible insects, especially species from the order Orthoptera (grasshoppers, crickets, and locusts) are rich in proteins and represent a valuable alternative protein source. Protein contents up to 77% (on a dry matter basis) have been reported for several grasshopper species (Ramos-Elorduy et al., 1997, 1998, 2007). The great



Cockroach Caterpillar Damsfly Bee Cricket Beetle

potential of insects as an alternative protein source becomes apparent when comparing with plant protein sources, such as dry soybeans with a protein content of 35.8%. However, the nutrient quality, digestibility, and availability in food of the insect proteins need to be assessed. Several studies (Ozimek et al., 1985; Finke et al., 1989) showed that the protein quality of insects is promising regarding availability and digestibility compared with casein and soy but varies and can be improved by the removal of the chitin. More research on the quality of insect proteins is required. This includes the amino acid spectra of edible insects and their suitability for human nutrition.

Amino acid composition of edible insects differs largely among species and orders. Nevertheless, on average, amino acid composition of edible insects described in the literature meets the amino acid requirements of human adults (in mg/g protein) for methionine (16 mg/g protein) and methionine + cysteine (22 mg/g protein), with one exception (flies) for cysteine (6 mg/g protein) according to the World Health Organization (WHO, 2007). Aside from the order Hemiptera (true bugs) being low in isoleucine, lysine, phenylalanine + tyrosine, and valine and the order Diptera (flies) being low in leucine and cysteine, in general, most edible insects satisfactorily provide the essential amino acids required for human nutrition according to the WHO (2007). High amino acid values have been found for phenylalanine + tyrosine in some species, and some insects are rich in tryptophan, lysine, and threonine (Rumpold and Schlüter, 2013).

Lipids

In addition to protein, the other main component in the nutrient composition of edible insects is fat. On a dry matter basis, the average fat content

Table 1. Average nutrient composition and energy contents of edible insect orders (on a dry matter basis). Adapted from Rumpold and Schlüter, 2013.

Nutrients and energy*	Cockroaches (*Blattodea*)	Beetles (*Coleoptera*)	Flies (*Diptera*)	Beetles (*Hemiptera*)	Bees, wasps, ants (*Hymenoptera*)	Termites (*Isoptera*)	Caterpillars (*Lepidoptera*)	Dragonflies (*Odonata*)	Grashoppers, locusts, crickets (*Orthoptera*)
Data amount n	3	45	6	27	45	7	50	2	51
Protein, %	57.30	40.69	49.48	48.33	46.47	35.34	45.38	55.23	61.32
min	43.90	8.85	35.87	27.00	4.90	20.40	13.17	54.24	6.25
max	65.60	71.10	63.99	72.00	66.00	65.62	74.35	56.22	77.13
SD	11.71	15.61	13.12	15.09	15.19	15.91	15.56	1.40	14.65
Fat, %	29.90	33.40	22.75	30.26	25.09	32.74	27.66	19.83	13.41
min	27.30	0.66	11.89	4.00	5.80	21.35	5.25	16.72	2.49
max	34.20	69.78	35.87	57.30	62.00	46.10	77.17	22.93	53.05
SD	3.75	18.91	9.35	18.74	11.96	9.05	17.89	4.39	10.90
Fiber, %	5.31	10.74	13.56	12.40	5.71	5.06	6.60	11.79	9.55
min	3.00	1.40	9.75	2.00	0.86	2.20	0.12	9.96	1.01
max	8.44	25.14	16.20	23.00	29.13	7.85	29.00	13.62	22.08
SD	2.81	6.50	2.81	5.74	6.32	2.47	5.15	2.59	4.23
NFE, %	4.53	13.20	6.01	6.08	20.25	22.84	18.76	4.63	12.98
min	0.78	0.01	1.25	0.01	0.00	1.13	1.00	3.02	0.00
max	10.09	48.60	8.21	18.07	77.73	43.30	66.60	6.23	85.30
SD	4.91	12.33	3.25	5.93	20.56	17.16	19.81	2.27	17.22
Ash, %	2.94	5.07	10.31	5.03	3.51	5.88	4.51	8.53	3.85
min	2.48	0.62	5.16	1.00	0.71	1.90	0.63	4.21	0.34
max	3.33	24.10	25.95	21.00	9.31	11.26	11.51	12.85	9.36
SD	0.43	4.83	8.14	5.44	1.56	3.98	2.65	6.11	1.65
Energy, Kcal/100g		490.30	409.78	478.99	484.45		508.89	431.33	426.25
min		282.32	216.94	328.99	391.00		293.00	431.33	361.46
max		652.30	552.40	622.00	655.00		776.85	431.33	566.00
n (Energy)	0	17	3	18	28	0	30	1	16
> 400 kcal/100g		13	2	13	27		25	1	9
> 500 kcal/100g		10	1	8	7		16	0	2
SD		111.42	173.28	98.53	58.88		114.10	0.00	63.70

*n = amount of data, min = lowest value, max = highest value, SD = standard deviation, and NFE = nitrogen-free extract.

ranges from 13.4% for grasshoppers, crickets, and locusts (Orthoptera) to 33.4% for beetles and their larvae (Coleoptera). Bugs (Hemiptera), termites (Isoptera), cockroaches (Blattodea), and some caterpillars (Lepidoptera) are also rich in fat with average amounts of 30.3, 32.7, 29.9, and 27.7% (on a dry matter basis), respectively, as shown in Table 1. The caterpillar *P. triangularis* (Lepidoptera) with approximately 77% fat (Ramos-Elorduy et al., 1997, 1998), the palm weevil larvae *Rhynchophorus phoenicis* (Coleoptera) with up to 70% fat (Omotoso and Adedire, 2007), and the wasp *P. instabiliz* (Hymenoptera) with 62% fat (Ramos-Elorduy et al., 1997), on a dry matter basis, are edible insect species with high fat contents. These "high-fat insects" can be used, for example, as energy supplements in high-energy diets due to their high caloric values. Furthermore, an oil extraction could be interesting for insect oils with nutritionally advantageous fatty acid spectra.

The fatty acid profile of edible insects predominantly collected in the wild reported in the literature shows that, saturated fatty acids (**SFA**) range from 31.8% for bees, wasps, and ants (Hymenoptera) to 42.0% for termites (Isoptera). Monounsaturated fatty acids (**MUFA**) range from 22.0% for termites (Isoptera) to 48.6% for bees, wasps, and ants (Hymenoptera) whereas polyunsaturated fatty acids (**PUFA**) range from 16.0% for flies (Diptera) to 39.8% for caterpillars of butterflies and moths (Lepidoptera). Some species of the orders Orthoptera (grasshoppers, locusts, and crickets) and Lepidoptera (caterpillars) were particularly high in PUFA (Rumpold and Schlüter, 2013). As observed in conventional livestock, fatty acid composition of edible insects depends on their feed composition. For example, feeding fish offal to black soldier fly larvae resulted in a significant enrichment in lipids, especially polyunsaturated omega-3-fatty acids, eicosapentaenoic acid (**EPA**), and docosahexaenoic acid (**DHA**) (St-Hilaire et al., 2007).


Moth Taco

The cholesterol content also depends of the insects' diets. Insects cannot synthesize cholesterol de novo but convert plant sterols from their diet to cholesterol. In addition, some insect species like the honey bee *A. mellifera* are not able to convert the plant sterols to cholesterol, and insects naturally feeding on diets containing other sterols than 5-sterols lack cholesterol (Ritter, 1990). Cholesterol content (based on fresh weight) of insects collected in Thailand is high—105 mg/100 g for house crickets, 66 mg/100 g for Bombay locusts, and 56 mg/100 g for scarab beetles (Yhoung-aree, 2010)—whereas total cholesterol contents of four insect species (*Imbrasia belina*, *Rhynchophoris phoenicis*, *Macrotermes bellicosus*, and *Oryctes rhinoceros*) consumed in Southern Nigeria are considerably less (Ekpo et al., 2009). By comparison, large fresh, raw eggs contain 372 mg/100 g, more than three times as much cholesterol as insects (Yhoung-aree, 2010). This leads to the conclusion that cholesterol-free insects could be produced if reared on specific diets.

Micronutrients

Generally, it is assumed that the micronutrient content in edible insects can be influenced by the diet. A compilation of 85 mineral compositions of edible insects (Rumpold and Schlüter, 2013) showed such huge variations within the same species that calculating mean values per insect order is not meaningful. Nevertheless, consumption of edible insects could provide significant amounts of copper, iron, magnesium, manganese, phosphorous, selenium, and zinc.

In addition to minerals, insects can also supply several vitamins. With regard to vitamin requirements for human adults recommended by the FAO (2004), reported riboflavin, pantothenic acid, and biotin contents are high. Grasshoppers, crickets, locusts (Orthoptera), and beetles and their larvae (Coleoptera) are also rich in folic acid. On the other hand, insects are, in general, not a good source of vitamin A, vitamin C, niacin, and, in most cases, thiamin and vitamin E with regard to the aforementioned vitamin requirements recommended by the FAO. It is concluded that some insect species have the potential to supply significant amounts of vitamins to human adult diets (Rumpold and Schlüter, 2013).

Anti-nutrients

Regarding the safe utilization of edible insects in food and feed, anti-nutrients and otherwise harmful substances have also to be considered. Chemical analyses of several edible insect species for anti-nutrients such as oxalate, phytate, tannin, and hydrocyanide resulted in amounts within nutritionally acceptable levels far below toxic levels (Omotoso, 2006; Ekop et al., 2010). On the other hand, the pupae of the African silkworm *Anaphe* spp. contain a heat-resistant thiaminase that has been responsible for thiamin deficiency in Nigeria (Nishimune et al., 2000). In addition, there are also insect species that biosynthesise toxins such as some cyanide-producing butterflies and beetle species (Blum, 1994). This needs to be taken into account for the identification of promising species to be used in human and animal nutrition.

Furthermore, there is evidence that the consumption of insects can cause allergic reactions comparable to allergies to crustaceans and house dust mite. This is mainly due to the presence of tropomyosin and arginine-kinase, well-known allergens in arthropods that are also present in insects. Furthermore, cross-reactivity studies suggest that patients allergic to house dust mites and crustaceans may react to food containing yellow mealworm proteins (Verhoeckx et al., 2014).

Risks related to extrinsic hazards due to contamination of edible insects with toxins, heavy metals, and pesticides sequestered via feed uptake, contaminations with human pathogens and microorganisms causing food spoilage, and toxins produced by microorganisms such as botulinum and mycotoxins also need to be considered.

In summary, edible insects are highly nutritious. However, for an extensive and safe utilization of insects as food and food ingredients, topics such as allergenic and toxic risks as well as presence of anti-nutrients need to be addressed. It is mandatory to know the chemical composition of insects to select the most appropriate species to be reared as food and feed. In addition, research is required on the impacts of rearing and feed substrates on the nutrient composition of insects. Furthermore, to ensure food safety and shelf-life stability, safe rearing conditions and effective decontamination procedures need to be defined.

Food Processing of Edible Insects

Steaming, boiling, baking, deep-frying, sun-drying, smoking, and processing into chutney or a paste are traditional preparation methods of edible insects described in the literature (Rumpold et al., 2014). The majority of insects consumed up to today are gathered in the wild (van Huis et al., 2013) and either eaten raw, prepared at home, or sold in local markets. Consequently, a tremendous amount of research is still needed on the production and processing methods on an industrial scale as well as on the microbial safety and decontamination of edible insects.

For the production of edible insects on an industrial scale, several factors need to be addressed. This includes the automation of farming and processing methods to enable a continuous production of insects in large quantities and high quality at competitive costs. To achieve a consumable form, automated preparation steps such as the removal of heads and legs are also needed for certain insect species. In addition, the development of national and international regulations and guidelines is necessary (van Huis et al., 2013). Examples for industrial-scale insect farming include AgriProtein in South Africa, Enviroflight in Ohio, USA, and HaoCheng Mealworms Inc. in China. The former two companies are feed producers where the insect larvae are dried and milled upon harvesting, whereas HaoCheng Mealworms Inc. produces and sells the insects alive, dried, canned, and in a powder form as food and feed ingredients (van Huis et al., 2013).

The impact of processing methods on the nutritional or functional qualities of insects and their components in food also need to be considered and determined. For example, Mariod et al. (2010) investigated the influence of extraction methods on the yield and oil quality such as the tocopherol content of the beetle *Agonoscelis pubescens*. Valle et al. (1982) examined the protein extraction of the Mexican fruit fly *Anastrepha ludens* and discovered negative effects of a drying step on the foaming and emulsifying capacities of the extracted protein isolate and concentrate. Insect processing could lead to novel insect-based food ingredients with unique functional properties and the innovative application of insect proteins, polysaccharides, and other insect components in food as texturizing agents for example. Potential functional properties of insects and their components have so far gained little attention although they could offer a huge potential for development of the food/feed industry.

Conclusions

Although there is still extensive research required on the nutrient composition of edible insects, it is undisputed that they represent an alternative sustainable source for animal-related protein for food and feed in general. Insects are generally rich in protein and fat and can provide essential amino acids, unsaturated fatty acids, and micronutrients.

Fried insects, street food at Central Market of Cambodia.

Major hurdles for the use of insects as food and feed in the Western hemisphere include legal barriers and an assumed lack of consumer acceptance. Both issues could be overcome with the help of sound scientific knowledge on beneficial properties and safety risks of edible insect species as well as development of effective and scientifically proven safety procedures. Production of high quality insect-based food products also requires studies on the impact of farming conditions and processing methods on nutritional quality and functional properties.

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