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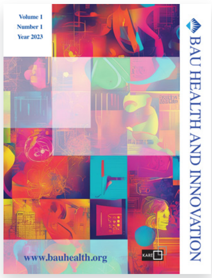

Review

As a Sustainable Alternative: Edible Insects

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Abstract

The rapid increase in the global population brings environmental problems, along with increasing demand for food. Sustainable nutrition refers to an approach to nutrition that aims to protect social and environmental sustainability and conserve food resources for future generations. Edible insects have the potential to be a sustainable food source as they have lower environmental impacts compared to other animal protein sources. In addition, studies examining the nutritional value of edible insects show that they have high nutritional values. However, there are some cultural, health, and hygiene concerns regarding the consumption of edible insects. These concerns suggest that edible insects could be a solution to global food demand if appropriate measures are taken for their safe consumption.

Keywords: Alternative food, edible insects, sustainable nutrition.

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It is predicted that the world population, which has been increasing since the 20th century, will reach 8.5 billion in 2030 and 9.7 billion in 2050.[1] The inability to reabsorb the greenhouse gases released into the atmosphere as a result of increased use of fossil fuels, along with population growth causes the global climate to change rapidly.[2] Producing sustainable solutions for climate change and other global environmental issues is necessary to ensure that future generations can also benefit from natural resources and to prevent hunger. The concept of sustainability was first addressed in the "Our Common Future" (Brundtland Report) published by the World Commission on Environment and Development in 1987. In this report, sustainability is defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".[3] Sustainable nutrition, on the other hand, is diets with low environmental impacts that provide both food and nutrition security, contributing to the healthy life of future generations.[4] Therefore, to reduce the negative effects of the environment, it is necessary to turn to alternative food sources and different nutritional models that have positive effects for the environment and individuals.[5] To combat the shortage of food resources and environmental problems, edible insects are a promising alternative food source due to their low cost, high nutritional composition, and sustainable production.[6] The use of insects as food (entomophagy) is widely influenced by cultural and religious practices and is a common and accepted diet in some societies, while in others (especially in Western countries), it is regarded with disgust and seen as a primitive behavior.[7] Although there are different approaches to entomophagy in society, it is used in more than one industry due to its advantages in terms of health, environment, and economy.[8] Although studies have shown that edible insects can be a solution to both meet global food demand and prevent malnutrition, more research is needed on this subject.[9,10]

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In this review article, the human health and environmental advantages of edible insects, which have a significant impact on sustainable nutrition and are used as an alternative food source in many countries, and their relationship with sustainable nutrition, were examined.

Entomophagia and Consumer Attitudes

Entomophagy is a term of Greek origin, consisting of the words "entomo" (insect) and "phagein" (food). This term refers to the acceptance and consumption of insects as food.[11] Entomophagy is commonly observed in the diets of societies where access to animal protein sources is difficult (such as ethnic groups living in Africa, Asia, and Latin America).[12] In Western societies, however, edible insects are generally not experienced as food.[13] Until now, the deliberate consumption of edible insects has been limited to special places such as experimental restaurants.[14] Although edible insects are a sustainable food source, there are some obstacles to their widespread use as human food.[15] The disgust factor is one of the main obstacles. In Darwin's study on basic emotions, disgust is considered one of the universal emotions and is a common experience for all humanity.[16] The feeling of disgust, which is one of the obstacles to the use of insects as food, is more commonly observed in Western societies than in other societies.[7] In this context, according to a study conducted in Brazil in 2023, the most frequently used word to express reluctance to eat insects was "disgust".[17] In another study conducted among German and Chinese individuals on insect-eating behaviors toward consumer attitudes, it was found that Chinese participants evaluated all insect-based foods more positively in terms of taste, nutritional value, disposition, and social acceptance, and were more willing to eat the tested products, compared to German participants.[18]

Nutritional Value of Edible Insects

Globally, 31% of the most commonly consumed insects are *Coleoptera* (beetles), 18% are *Lepidoptera* (scale-wings), 14% are *Hymenoptera* (membrane-wings), and 13% are *Orthoptera* (flat-wings). Other edible insects are *Hemiptera* (half-wings), *Isoptera* (termites), *Odonata* (helicopter beetles), *Diptera* (biptera), and other species.[19] The order Coleoptera, consisting of 300 and 50,000 species of insects, is the largest animal order in the world. This order includes 659 insect species that are consumed primarily in the larval stage.[20] The order *Orthoptera* includes commonly known insects such as crickets and *grasshoppers*. Crickets from the order *Orthoptera* and yellow mealworms from the order *Coleoptera* are the most popular insects raised for human consumption.[21]

The nutritional components of various insect species are shown in Table 1.[22] The nutritional value of edible insects varies according to their species and metamorphosis stage. In edible insects, protein and fat are more abundant in dry matter, while moisture content is highest in fresh weight. Insects with lower moisture content have higher fat content. They also contain carbohydrates (especially chitin) and many micronutrients.

Protein Content

The protein content of most insects is higher than that of plant proteins (cereals and legumes). Order-wise, *Orthoptera* generally have higher protein content compared to other insect orders (Fig. 1).[23–25] Almost all edible insect species contain adequate amounts of amino acids such as phenylalanine, tyrosine, tryptophan, threonine, and lysine at levels comparable to meat and meat products.[26] For example, beef has higher amino acid content in glutamic acid, lysine, and methionine and lower amino acid content in isoleucine, leucine, valine, tyrosine, and alanine compared to mealworm (*Tenebrio molitor* -TM).[27] A study has shown that insect proteins have a high digestibility by humans. Therefore, it is thought that the consumption of edible insects can significantly improve the diet quality of individuals and contribute to total protein intake.[28]

Fat Content

Edible insects are an important source of fat.[29] The total fat content of insects ranges from 2% to 62%.[22] The total content of cholesterol and fatty acids in insects can vary greatly depending on their species and stages of metamorphosis[30] and diet.[31] The fat content of larvae of *Lepidoptera* and

Table 1. Nutritional components of edible insects

Protein	Fat	Carbohydrate	Vitamin	Mineral	Other
Active peptides, Amino acids	Saturated fatty acids, Unsaturated fatty acids	Cellulose, Chitin, Chitosan	Riboflavin, Cobalamin, Niacin, Pyridoxine, Vitamin A, Vitamin E	Calcium, Zinc, Phosphorus, Iron, Copper, Selenium	Lecithin, Cellulose, Zeaxanthin, b-Carotene

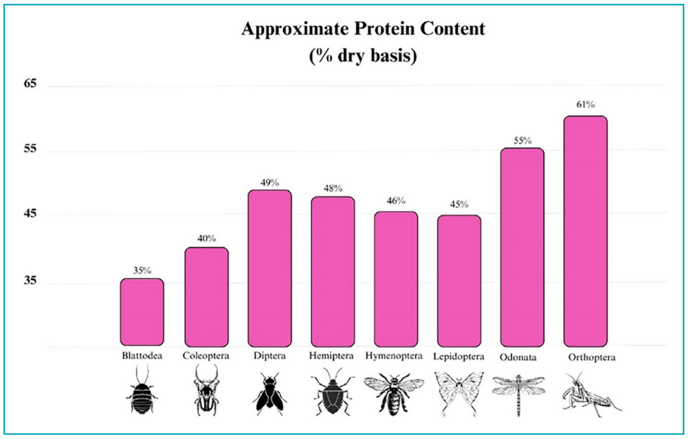

Figure 1. Approximate protein content for the eight most common orders of edible insects.

Heteroptera (suborder *Hemiptera*) is higher than that of other edible insects.[8] It mainly contains polyunsaturated fatty acids such as linoleic and α-linolenic acid. The profile of fatty acids in insects is generally similar to that of animal and vegetable oils.[32] Terrestrial insects are reported to contain higher amounts of long-chain polyunsaturated fatty acids, especially omega-6 fatty acids, than aquatic insects.[33]

Micronutrient Content

A few data are available on the micronutrient content of insect species.[25,34] The mineral and vitamin contents of edible insects described in the literature vary considerably among species and orders.[7] This is due to factors such as insect species, metamorphosis stage, genetic factors, feeding habits, gender, environmental conditions, geographical location, soil composition, plant species, and processing methods, which significantly affect their nutrient composition.[35] In addition, consuming the whole insect is thought to provide higher micronutrient content than eating individual insect parts.[7]

Mineral content

The iron content of edible insects is quite high. Some insect species, such as *grasshoppers*, cockroaches, and spiders, can contain iron levels equal to or higher than beef.[36] However, the iron bioavailability of insects can be lower than that of plant and other animal-based foods. Edible insects are also rich in minerals such as zinc, copper, and manganese. Crickets and *grasshoppers* in particular have also been shown to be rich in magnesium.[25] Cricket dust contains high levels of magnesium, copper, and zinc.[37] It is known that the amounts of calcium, copper, magnesium, manganese, and zinc in mealworms (*Tenebrio molitor*) and *grasshoppers* (*Sphenarium purpurascens*) are higher than in beef.[38] In addition, low sodium concentrations have led to the idea of including edible insects in low-sodium diets.[25]

Vitamin content

Although there are not enough studies on the vitamin content of edible insects, B complex vitamins (riboflavin, pantothenic acid, and biotin) are found at relatively high levels in various species.[25,39] However, B12 levels are quite low in many species and they are not a good source of Vitamins A and C.[25,40]

Fiber Content

The most common form of fiber in edible insects is chitin, an insoluble fiber.[41] Chitin is a long-chain N-acetylglucosamine polymer that forms the exoskeleton of many insects, approximately 10% of dry weight.[28,42] The chitin content of edible insects depends largely on the insect species and developmental stage. In commercially reared insects, chitin is found between 2.7 and 49.8 mg per fresh weight and 11.6–137.2 mg per dry weight.[41] Chitin cannot be digested by humans, but the enzyme chitinase can be found in the gastric fluid of some people.[43] Chitinase activity is more common in tropical countries where insects are regularly consumed than in Western countries (due to the absence of chitin in their diets). Chitin may be effective in protecting some organisms against parasitic infections and allergic conditions. It can also contribute to the healthy development of the gut microbiota by exerting a probiotic effect. Therefore, it can be said that chitin acts as a dietary fiber.[25,44]

Bioactive Component Content

Edible insects contain bioactive components that can provide various bioactivities that have a positive effect on human health. Bioactive components have antioxidant, antihypertensive, anti-inflammatory, antimicrobial, and immunomodulatory activities.[6] Many edible insect species, including crickets, silkworms, and *grasshoppers*, have been reported to have antioxidant capacities 2–3 times higher than olive oil or orange juice, as shown in their juices and oil-soluble extracts.[45] It is also known that some insects contain phenolics and flavonoids. High levels of these compounds, such as those found in silkworm larval powders, may exert positive effects on health through their antioxidant properties.[46,47]

Some Food Studies with Edible Insects

In a study by Ho et al. (2022),[48] sausage, pasta, and cakes were produced by enriching 10% of lean meat with cricket powder, and the quality, nutritional content, and consumer expectations of the products were evaluated. It was determined that the sausage enriched with cricket powder had higher carbohydrate, lower fat, and moisture content compared to the control (70% lean meat and 30% lard) ($p < 0.05$). However, there was no difference in ash and protein between control and cricket powder-enriched sausage ($p > 0.05$). For both raw sausage and cooked sausage patties, there was a noticeable difference between the two versions. The sausage enriched with cricket powder had significantly higher cooking efficiency than the control ($p < 0.05$). When evaluated for textural properties, it was determined that the elasticity increased with enrichment with cricket powder ($p < 0.05$). As a result of the study, it was determined that the use of cricket powder in sausage making can reduce the use of lean meat and maximize the use of cricket powder without significant changes in sensory and quality characteristics. In pasta making, dried fresh fettuccine pasta was developed using a durum wheat-based formulation. For control pasta, 14% of the durum wheat semolina was replaced with whole wheat flour, while in making pasta enriched with cricket powder, 5% of the durum wheat semolina was replaced with cricket powder. Considering the nutritional components, an increase in both protein and fat content and a decrease in carbohydrate content of pasta enriched with cricket powder was detected ($p < 0.05$). For textural properties, no difference was detected in terms of firmness, stickiness, and flexibility ($p > 0.05$). No color difference was observed between the uncooked cricket powder-enriched pasta and the control group, while a color difference was observed between the cooked cricket powder-enriched pasta and the control group. As a result, it has been determined that adding insect powders to wheat-based staple foods such as pasta may be a suitable option to increase the nutritional profile. Finally, a cricket powder enriched cake formulation was developed by replacing 7% of wheat flour with cricket powder. The protein and fat content of the cricket powder-enriched cake was significantly higher and the carbohydrate content was significantly lower compared to the control ($p<0.05$). No difference was found between the control and cricket powder-enriched cake in terms of moisture content and ash ($p > 0.05$). For textural properties, the chewiness of the control cakes was higher than that of the cricket powder-enriched cakes, while no difference was found for firmness and stickiness ($p > 0.05$). It is estimated that this may be due to the low level of wheat flour in the cake enriched with cricket powder. It was thought that cricket powder may have acted similarly to wheat bran by causing gluten dilution and limiting gluten formation in the product. As a result, considering that cake is a high-calorie food product, it is thought that the increase in protein amount with enrichment may be attractive to some consumers.

Zielińska et al. (2020)[49] investigated to what extent the replacement of wheat flour and butter with a portion of mealworm (*Tenebrio molitor-TM*) flour can affect the nutritional, physiochemical, and antioxidative properties of shortcake biscuits. For the control group, wheat flour (300 g), butter (150 g), egg (60 g), and sugar (70 g) were used without the addition of insecticide. In the enrichment groups, the amount of *TM* flour and butter were used as 30g/135g (M1), 20g/140g (M2), and 15g/142.5g (M3), respectively. These modifications were examined in terms of properties such as nutritional values, physical properties, and color, which change with the increase in the proportion of *TM* flour. The highest color difference compared to the control was observed in the M1 sample containing the most *TM* flour. The protein content in *TM* flour was higher than wheat flour, which resulted in a higher degree of Maillard reaction with increased surface redness. Antioxidant activity was shown to increase with the addition of *TM* flour. During *in vitro* digestion of mealworm, it was confirmed that peptides with strong antioxidant properties were released. In starch digestibility, the levels of rapidly digested starch determined *in vitro* decreased and the levels of slowly digested starch increased. This study showed that edible insects can be a good source of nutrients and a bioactive additive in foods for making various food products.

Another study conducted by Djouadi et al. (2022)[50] aimed to develop new modifications by incorporating mealworm meal (*TM*) into salty snacks (crackers) that can be used as an alternative protein source. In F2, F3, F4, F4, F5, F6, and F7 formulations enriched with *TM* flour, 2%, 4%, 6%, 10%, 15%, and 20% *TM* flour was used, respectively. It was observed that the cookie darkened as the amount of *TM* flour increased. A significant decrease was observed in the water content of the cracker enriched with *TM* flour compared to the control. No significant difference was observed between the control and enriched crackers in terms of fat content ($p > 0.05$). The protein content in crackers enriched with 6% *TM* flour increased by 4.3% compared to the control. Since pure *TM* flour is a source of potassium, magnesium, phosphorus, and iron, these minerals were higher in crackers enriched with *TM* flour compared to the control group. Since pure *TM* flour is a source of potassium, magnesium, phosphorus, and iron, these minerals were higher in crackers enriched with *TM* flour compared to the control group. While crackers containing 20% *TM* flour were not considered sensory acceptable because they had a very dark and bitter taste, 70% of the panelists reported that they would be willing to buy crackers containing 6% *TM* flour and 60% would not buy crackers containing 15% *TM* flour. The results of this study showed that *TM* flour can be recommended as an ingredient that can be used to enhance the nutritional profile of a food.

There are also intervention studies in which the effects of adding edible insect-based food products to individuals' diets on nutritional status, microbiota, and anemia are evaluated. In a randomized control study conducted by Homann (2015), the acceptability of cricket (*Acheta domesticus*)-based biscuits and their effect on intestinal microbiota composition were evaluated to improve the nutritional status of children in Kenya. Fifty-four children aged 5–10 years were asked to consume 98–102 g of biscuits containing 10% cricket powder (intervention) or 10% milk powder (control) on school days for 4 weeks. As a result, it was determined that the effect of biscuits containing cricket powder on the microbiota composition compared to milk biscuits did not differ between the intervention and control groups. They also had lower hedonic evaluations.[51] Another study examining the effects of cricket powder consumption on the gut microbiota in healthy adults evaluated individuals who consumed breakfast foods containing or not containing crickets (control) for 14 days. It has been observed that consumption of 25 g of cricket powder is tolerable and has no toxic effects. Cricket powder increased the growth of probiotic bacteria *Bifidobacterium animalis* by 5.7-fold. Cricket consumption has also been associated with decreased plasma TNF-α.[52]

A single-blind, randomized, and controlled study by Kipkoech (2019) examined the nutritional composition and prebiotic potential of chitin from farm-raised crickets (*Acheta domesticus*) and its availability to improve growth, hemoglobin, and fatty acid levels of children in Kenya. One hundred and thirty-eight children aged between 3 and 4.5 years were fed corn millet (MMP), corn millet with skimmed milk (MP10), or 5% cricket-based porridge (CP5) for 6 months. It was seen that the anthropometric measurements of all children in the three groups improved. Weight-for-age z-score increased from −1.0 to 0.39, 035, and 0.41 in MMP, MP10, and CP5, respectively. A significant difference was also detected in fatty acids and hemoglobin levels. Therefore, it has been reported that cricket-based porridge can improve the nutritional status of children.[53]

In a randomized, double-blind, and controlled study conducted by Konyole et al. (2019),[54] locally produced WinFood Classic (WFC), which contains 10% edible termite (Macrotermes subhylanus), and WinFood Lite (WFL), which does not contain edible insects, were tested for 6 months. Its effect on fat-free mass (FFM) accumulation, linear growth, and iron status in 499 Kenyan infants was evaluated by comparing it to a standard product, corn-soy blend plus (CSB+). The follow-up of the study lasted 15 months. As a result, no difference in FFM gain and height was found in the insect-based trial group (WFC) compared to the other two non-insect-based food trial groups (WFL and CSB+). However, a decrease in plasma ferritin levels, an increase in plasma ferritin receptors, and a decrease in hemoglobin concentration were observed.

Another randomized and controlled study evaluated the effect of caterpillar flakes on reducing stunting and anemia in infants in the Democratic Republic of Congo. In an 18-month follow-up of 175 6-month-old babies, consumption of caterpillar flakes was found to reduce the prevalence of stunting in infants and reduce the prevalence of anemia by increasing hemoglobin concentrations.[55]

Processing of Edible Insects

Edible insects, like other animal products, are rich in nutrients and moisture, and under certain conditions can be a breeding ground for undesirable microorganisms.[56] Although they are rich in nutritional value, they can be contaminated with natural poisons or agrochemicals before they pose a serious risk to human health. Furthermore, without proper heat treatment or storage conditions, insects become susceptible to microbiological hazards. Therefore, care must be taken when processing and storing edible insects. Therefore, care must be taken in the handling and storage of edible insects. Before edible insects and their use in food and feed, potential safety issues for the health of consumers and animals should be identified and microbiological, chemical, toxicological, and allergic risks should be reduced. Food safety should be ensured and quality should be maintained by processing with the most appropriate methods.[57] The nutrient composition, digestibility, and bioavailability of insects may vary depending on the processing conditions, methods of obtaining, and cooking.[7] For example, raw insects have higher *in vitro* digestibility compared to boiled or roasted insects.[58] Some studies have also shown a decrease in crude protein, ash, and zinc contents after cooking.[22,42] Similarly, Bukkens (1997) showed that mopane worms had a lower protein content when dry roasted compared to when dried (48% and 57%, respectively). This was also the case for termites. While the protein content was 20% in raw termites, it was found to be 32% of its fresh weight when fried and 37% when smoked.[59]

Processing methods are divided into traditional and industrial. In the traditional method, the first step is cleaning. This is a process to remove foreign materials. Depending on the species, the heads, wings, legs, and intestines of the insects need to be removed and cleaned with water.[35] Industrial processing methods of insects are similar to traditional

Table 2. Efficiencies of traditional meat and cricket production

	Cricket	Poultry	Pork	Beef
Feed conversion ratio (kg/kg live weight)	1.7	2.5	5	10
Edible part (%)	80	55	55	40
Feed (kg/kg live weight)	2.1	4.5	9.1	25

methods. However, unlike traditional methods, industrial processes are carried out under control. For example, after processes such as boiling, pasteurization, sterilization, and drying, the purified insects are dried and ground to produce insect flour or insect-based products. In addition, protein, fat, and chitin, the main components of insects, can be extracted for use as ingredients in some food products.[58,60]

Edible Insects and Sustainablity

Negative impacts on the environment are increasing due to the increasing population, consumer demands, and water and land use worldwide. Any increase in animal production requires additional feed and agricultural land. Edible insects contribute positively to sustainability in terms of nutrition and environmental health as they generate less waste, ammonia, and greenhouse gases and use less land and energy.[61]

Insect farms require much less land and resource use than traditional animal farming, which can help reduce deforestation and preserve biodiversity (Table 2).[57] In addition, insects can be grown in vertical farms and located in urban areas. This could provide opportunities for local food production and reduce the carbon footprint associated with transportation.[7]

Insects are cold-blooded creatures. Since they can meet their moisture needs from food, they do not need drinking water and their water footprint is lower. They can also grow and feed on organic waste.[62] Therefore, most species have nutritional value comparable to conventional animal meats on a gram basis and a higher feed conversion ratio to produce the same amount of protein.[6] Some species, such as *grasshoppers*, for example, consume 6 times less feed than cattle, 4 times less than sheep, and almost half as much as pigs and broiler chickens.[7]

When the carbon footprint of edible weight is calculated with the data mentioned above, it can be said that crickets are twice as efficient as chickens, 4 times more efficient than pigs, and 12 times more efficient than cattle. Since the whole animal is usually not eaten, the advantage of edible insects becomes even greater as these ratios are adjusted based on edible weight.[57]

In addition to resource and land consumption, environmental impacts related to greenhouse gas production should also be considered. Controlling greenhouse gas and ammonia emissions is crucial for environmental protection and sustainability. The Food and Agriculture Organization emphasizes that the global livestock industry is responsible for 14.5% of global greenhouse gas emissions.[63] Compared to pigs and cattle, edible insects emit approximately 100 times less greenhouse gases.[7] Therefore, insects are a more sustainable option compared to traditional animals. In a different study, it was determined that reared insects used 15 m^2 of land to produce 1 kg of protein and 200 m^2 of land for cattle. It has been observed that they have lower greenhouse gas and ammonia emissions per unit protein and use fewer resources.[24] However, there is also a large difference in emissions between different insect species.[63]

Conclusion

It is predicted that global food demand will increase by more than 50% by 2050 compared to today. This situation is becoming a significant problem for global agricultural systems. As food resources are becoming limited, the search for solutions continues. Edible insects stand out as a promising food source in the future with their high nutritional value, especially protein content, requiring less land and resource use in their production compared to other animal protein sources, low greenhouse gas and ammonia emissions, and being suitable for vertical farming. The tendency for edible insects to be consumed by humans may vary depending on many factors such as gender, religious, and cultural factors. If people do not consume insects directly, it is thought that changing the form of insects (in flour or as food additives) may be a solution. Further, research on their nutritional value is needed to reduce people's concerns and promote edible insects more effectively as a healthy food source. At the same time, people should be informed that they are not only good for their health but also for future generations and the planet.

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