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Insect-Originated Functional Food: Nutritional Benefits and Applications

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Abstract

Functional foods, introduced in the early 1980s, offer health benefits beyond basic nutrition and are increasingly demanded due to growing consumer awareness of diet-health relationships. This review explores insect-based functional foods, highlighting their nutritional benefits, health implications, and applications. Edible insects, such as crickets, mealworms, and locusts, are rich in protein, healthy fats, vitamins, and minerals, making them a promising solution for food security and sustainability. Insect-based foods contribute to weight management, cardiovascular health, anti-inflammatory properties, gut health, and potential anti-cancer benefits. Despite most insects being low in calcium and potassium, they are high in phosphorus and, to a lesser extent, magnesium. Active components like royal jelly, bee pollen, and extracts from *Tenebrio molitor* and *Periplaneta americana L*. have shown potential in osteoporosis prevention by improving bone density and reducing bone resorption. Silk sericin-based functional foods also exhibit preventive and therapeutic effects against bone loss. However, challenges such as regulatory barriers, food safety concerns, consumer acceptance, potential allergenicity, and the need for standardization and quality control must be addressed. This review underscores the potential of insect-based functional foods in enhancing health and well-being, particularly for osteoporosis prevention, and highlights the need for further research and regulatory harmonization to facilitate their adoption.

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Introduction

Functional foods, a concept introduced in the early 1980s, refer to foods that provide health benefits beyond basic nutrition. These foods, often fortified or enhanced with bioactive compounds, play a crucial role in promoting optimal health and reducing the risk of chronic diseases (Topolska *et al*., 2021). The growing consumer awareness regarding the relationship between diet and health has led to an increased demand for functional foods, which are now a significant part of the global food industry (Lafarga *et al*., 2020).

Functional foods are defined as those that have a potentially positive effect on health beyond basic nutrition. They encompass a broad range of products, including conventional foods, fortified foods, and dietary supplements (Topolska *et al*., 2021). The importance of functional foods lies in their ability to address various health concerns such as osteoporosis, heart disease, diabetes, obesity, and digestive disorders (Essa *et al*., 2023).

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By incorporating functional foods into daily diets, individuals can enhance their overall well-being and prevent the onset of numerous health conditions.

In recent years, there has been a growing interest in insect-based foods as a sustainable and nutritious alternative to traditional animal-based protein sources (Mannaa *et al.*, 2023). This interest is driven by several factors, including the environmental impact of livestock farming, the need for efficient and sustainable food production systems, and the high nutritional value of insects (Mannaa *et al.*, 2023). Edible insects, consumed in various cultures for centuries, are rich in protein, healthy fats, vitamins, and minerals (Puteri *et al.*, 2023). They offer a promising solution to the challenges of food security and sustainability, making them an attractive option for functional food development.

The aim of this review is to explore the potential of insect-originated functional foods, focusing on their nutritional benefits, health implications, and applications in the food industry. This review will provide a comprehensive overview of the nutritional composition of edible insects and their health benefits. Additionally, it will address the economic and environmental considerations and challenges and barriers to acceptance. By compiling and analyzing the existing literature, this review aims to highlight the potential of insects as a viable and beneficial component of the functional food market.

Nutritional Composition of Edible Insects

Edible insects are renowned for their high protein content, making them an excellent alternative to traditional protein sources such as meat and dairy (Fig. 1). Most edible insects contain between 30-80% protein on a dry weight basis (López-Gámez *et al.*, 2024). The quality of insect protein is comparable to that of conventional animal proteins, as it includes all essential amino acids necessary for human health (Cunha *et al.*, 2023). The high digestibility and bioavailability of insect proteins further enhance their nutritional value, supporting muscle growth, repair, and overall metabolic function (Cunha *et al.*, 2023).

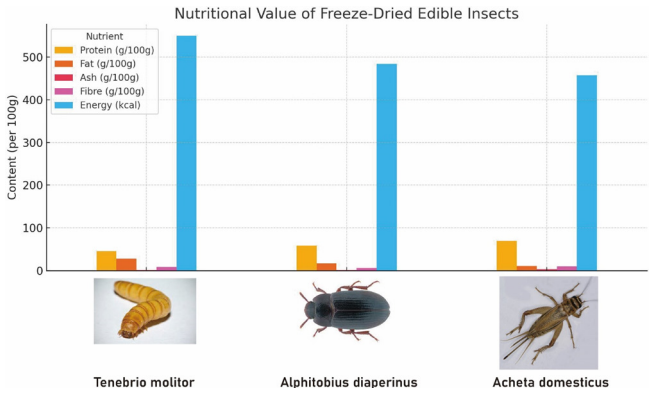

Fig. 1. Nutritional value of freeze-dried edible insects.

The amino acid profile of edible insects is well-balanced, providing all the essential amino acids in proportions that meet or exceed the requirements of the human diet. For instance, insects such as crickets, mealworms, and locusts are rich in lysine, leucine, and valine—amino acids that are critical for protein synthesis and muscle repair (Nowakowski *et al.*, 2022). This complete amino acid profile positions insects as a superior protein source, particularly in regions where protein malnutrition is prevalent (Table 1).

Table 1. Amino Acid Composition of Different Insect Species (mg/g)

Insect Order	His	Ile	Leu	Lys	Met	Cys	Phe	Tyr	Thr	Trp	Val
Blattodea	17.9	30.0	50.0	40.0	15.0	8.0	25.0	19.0	25.0	10.0	37.0
Coleoptera	20.1	28.0	45.0	30.0	13.0	8.0	27.0	19.0	24.0	12.0	34.0
Diptera	17.0	32.0	48.0	36.0	14.0	6.0	24.0	18.0	23.0	10.0	36.0
Hemiptera	19.0	26.0	44.0	32.0	13.0	9.0	25.0	21.0	22.0	11.0	32.0
Hymenoptera	18.0	31.0	47.0	35.0	16.0	7.0	28.0	20.0	24.0	11.0	35.0
Lepidoptera	19.0	29.0	46.0	34.0	15.0	9.0	26.0	20.0	23.0	11.0	34.0
Orthoptera	18.0	30.0	49.0	38.0	16.0	7.0	27.0	18.0	25.0	11.0	36.0

(Histidine (His), Isoleucine (Ile), Leucine (Leu), Lysine (Lys), Methionine (Met), Cysteine (Cys), Phenylalanine (Phe), Tyrosine (Tyr), Threonine (Thr), Tryptophan (Trp), and Valine (Val))

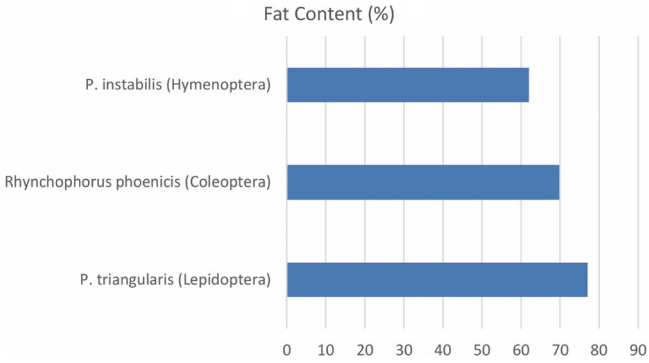

Fig. 2. Fat content of different insect species having high fat content.

In addition to being rich in protein, edible insects also contain significant amounts of fats, which contribute to their overall energy content (Fig. 1). The fat content of insects varies widely among species, ranging from 10-50% on a dry weight basis (Rumpold *et al*., 2013). These fats are not only a dense source of energy but also play a vital role in the absorption of fat-soluble vitamins and the maintenance of cell membrane integrity (Fig. 2).

Edible insects are a valuable source of polyunsaturated fatty acids, including omega-3 and omega-6 fatty acids (Nowakowski *et al*., 2022). These essential fatty acids are crucial for maintaining cardiovascular health, reducing inflammation, and supporting brain function. For example, mealworms and crickets are noted for their favorable ratio of omega-3 to omega-6 fatty acids, making them beneficial for heart health (Cholewski *et al*., 2018). The inclusion of these insects in the diet can help balance the intake of essential fatty acids, which is often skewed towards omega-6 in Western diets.

Insects also contribute dietary fiber, primarily in the form of chitin, a component of their exoskeleton (Barragán-Fonseca *et al*., 2022). Chitin and its derivatives, such as chitosan, have been shown to possess several health benefits, including prebiotic effects that promote gut health (Stull and Weir, 2023). These fibers can enhance digestive health by fostering a beneficial gut microbiota, improving bowel regularity, and potentially aiding in the management of weight and metabolic diseases (Ros-Baró *et al*., 2022). However, due to their high molecular weight, these proteins require appropriate processing to be utilized effectively as functional foods (Ratcliffe *et al*., 2011). Several green processing technologies have been introduced for manufacturing insect-based functional foods (Table 2).

Recent studies have highlighted the antioxidant properties of edible insects, attributed to their rich content of bioactive compounds (Nowakowski *et al*., 2022). These antioxidants help combat oxidative stress and reduce the risk of chronic diseases such as cancer and heart disease (Liguori *et al*., 2018). For instance, phenolic compounds and flavonoids found in honey produced by honeybee and stingless bee exhibit significant antioxidant activity (Ranneh *et al*., 2021). Incorporating honey into the diet can thus contribute to the body's defense against oxidative damage and support overall health (Ranneh *et al*., 2021).

In summary, the diverse and rich nutritional composition of edible insects or insects-derived product underscores their potential as functional foods. With high-quality protein, essential fatty acids, vitamins, minerals, fiber, and antioxidants, insects offer a comprehensive array of nutrients that can support health and well-being. As the global population seeks sustainable and nutritious food sources, edible insects present a promising solution to meet these demands.

Table 2. Summary of Green Processing Technologies

Technology	Description	Potential Benefits
High-Pressure Processing (HPP)	Utilizes high pressure to inactivate pathogens and preserve food.	Enhances safety and shelf life without altering nutritional and sensory properties.
Pulsed Electric Fields (PEF)	Applies short bursts of high voltage to food, leading to cell membrane permeabilization.	Improves extraction efficiency of bioactive compounds, enhances shelf life, and reduces drying time.
Ultrasounds (US)	Uses high-frequency sound waves to disrupt cell structures.	Increases extraction yield of nutrients and bioactive compounds, improves drying efficiency.
Cold Plasma (CP)	Involves ionized gas at low temperature for surface decontamination.	Reduces microbial load, extends shelf life, and preserves quality.
Enzymatic Hydrolysis (EH)	Uses enzymes to break down proteins into smaller peptides and amino acids.	Enhances protein solubility, improves functional properties, and may reduce allergenicity.

Health Benefits of Insect-Based Functional Foods

(1) Weight Management

Insect-based functional foods can play a significant role in weight management due to their high protein content and low carbohydrate levels. High-protein diets are known to increase satiety, reduce appetite, and enhance thermogenesis, which can aid in weight loss and maintenance (Skotnicka *et al.*, 2022). The protein in edible insects is also highly digestible and bioavailable, making it an efficient source of nutrition that can help in building and maintaining lean muscle mass while reducing fat accumulation. Additionally, the presence of fiber, such as chitin, may further contribute to satiety and improved digestion, supporting weight management efforts (Rehman *et al.*, 2023).

(2) Cardiovascular Health

The inclusion of insect-based foods in the diet can positively impact cardiovascular health. Edible insects are rich in unsaturated fats, particularly omega-3 and omega-6 fatty acids (Oonincx *et al*., 2020), which are known to improve heart health by reducing triglyceride levels, lowering blood pressure, and decreasing the risk of heart disease (Jain *et al*., 2015). The favorable lipid profile of insects can help manage cholesterol levels, promoting a healthy balance of low-density lipoprotein and high-density lipoprotein (Ros-Baró *et al*., 2022). Furthermore, certain bioactive compounds such as carvacrol in insects exhibit cardioprotective properties, enhancing overall cardiovascular function (Friedman 2014).

(3) Anti-inflammatory Properties

Edible insects or insects-derived food contain bioactive peptides and fatty acids that possess anti-inflammatory properties (Ranneh *et al*., 2021; Quinteros *et al*., 2022). Chronic inflammation is a common underlying factor in many diseases, including arthritis, diabetes, and heart disease. The consumption of insect-based foods can help modulate inflammatory responses and reduce inflammation-related symptoms. For instance, omega-3 fatty acids in insects can inhibit the production of inflammatory cytokines and eicosanoids, thus reducing inflammation and its associated risks (Simopoulos, 2002).

(4) Gut Health and Microbiota Modulation

Insect-based functional foods can positively influence gut health and the composition of the gut microbiota (Borrelli *et al.*, 2017). The fiber content in insects, particularly chitin, acts as a prebiotic, fostering the growth of beneficial gut bacteria (Zheng *et al.*, 2018). A healthy gut microbiota is essential for efficient digestion, nutrient absorption, and immune function (Adak and Khan, 2019). Improved gut health can also alleviate symptoms of gastrointestinal disorders such as irritable bowel syndrome (IBS) and inflammatory bowel disease (IBD) (Canakis *et al*., 2020). The modulation of gut microbiota by insect-based foods can enhance digestive health and overall well-being.

(5) Potential Anti-Cancer Properties

Emerging research suggests that insect-based functional foods may have potential anti-cancer properties (Ratcliffe *et al*., 2011). The bioactive compounds in insects, including peptides, polyphenols, and fatty acids, have shown promise in inhibiting cancer cell proliferation, and inducing apoptosis (programmed cell death) in various cancer cell lines. Additionally, the antioxidant properties of insects help protect cells from DNA damage and mutations that can lead to cancer. Immune-challenged *Bombyx mori* hemolymph extracts have antioxidant properties that downregulate sirtuin 5 and upregulate peroxiredoxin 1 expression in cells, suggesting their potential as an auxiliary treatment for drug-resistant tumors (Yun *et al.*, 2023). *Oxya chinensis sinuosa* hot water extract (OCH) shows potential as a natural therapeutic agent for benign prostatic hyperplasia (BPH) by inhibiting the androgen receptor signaling pathway and reducing the expression of BPH-related mRNA and proteins, suggesting its benefits in preventing and treating BPH with fewer side effects compared to chemical drugs (Lim *et al.*, 2023). While more research is needed to fully understand the mechanisms and efficacy, the initial findings are encouraging.

(6) Osteoporosis Prevention

Calcium, phosphorus, and magnesium are crucial for maintaining bone density and strength. However, most insects analyzed, except for larvae of the housefly (Musca domestica), are low in calcium and do not meet the required daily amount for adults (Rumpold and Schlüter, 2013). Additionally, 100 g of dried insects do not fulfill the daily requirement of 4700 mg for potassium (Rumpold and Schlüter, 2013). On the other hand, most insects contain very high amounts of phosphorus, with 24 out of 60 insects meeting the recommended dietary allowance for adults (Rumpold and Schlüter, 2013). For magnesium, only

23 out of 77 insects analyzed sufficiently supply this mineral (Rumpold and Schlüter, 2013). Accordingly, an approach focused on active components rather than mineral components appears to be more appropriate for investigating insect-based anti-osteoporosis therapy.

A study on the effects of royal jelly and bee pollen on bone loss in an oophorectomized rat model found that these substances significantly improved bone mineral density and increased bone calcium and phosphate levels (Kafadar *et al*., 2012). These findings suggest that royal jelly and bee pollen, alongside insect-based foods, can offer potential benefits for osteoporosis prevention and bone health maintenance. Kangfuxin (KFX), an ethanol extract of *Periplaneta americana L*. used in traditional Chinese medicine, has shown promising anti-osteoporosis potential by promoting osteoblast and endothelial cell activity while inhibiting osteoclast activity, thus enhancing bone formation, and reducing bone resorption (Huang *et al*., 2017). Novel compounds from *Tenebrio molitor* (TM) larvae exhibit anti-osteoporotic effects and prevent abnormal brain function by improving hypothalamic-pituitary-adrenal axis feedback and maintaining neurogenesis in the hippocampus (Kim *et al*., 2019). Daily administration of TM to ovariectomized mice for 4 weeks showed anti-osteoporotic effects and normalized brain environment (Kim *et al*., 2019). TM could serve as a bioactive supplement for bone and brain health in postmenopausal women. *Oxya chinensis sinuosa* ethanol extract shows promise in preventing osteoporosis by significantly inhibiting osteoclast formation and activity in receptor activator of nuclear factor kappa-B ligand-stimulated cells, reducing osteoclast-specific marker proteins, and suppressing the activation of p38 MAPK and JNK pathways, indicating its potential as a therapeutic agent (Choi *et al*., 2024).

Silk sericin, a natural protein from silkworm cocoons, is gaining recognition in biomedicine for its biocompatibility, biodegradability, and versatility in tissue engineering and wound healing. It enhances scaffold porosity and strength, expedites tissue healing, reduces bacterial load in wounds, and shows promise in bioactive dressings and peripheral nerve injury repair, indicating its broad applications and potential to improve patient outcomes in regenerative medicine (Kim *et al*., 2024). Silk sericin-based functional food (SSBF) has demonstrated preventive and therapeutic effects against bone loss (Jin *et al*. 2024). Sericin from *Bombyx mori* cocoons stimulated osteoblast differentiation and inhibited receptor activator of nuclear factor kappa-B ligand-induced osteoclast differentiation *in vitro* (Jin *et al*. 2024). In an ovariectomized mouse model, SSBF increased bone mass and enhanced osteoblast activity while suppressing bone resorption (Jin *et al*. 2024). These findings suggest that SSBF could be a promising candidate for preventing and treating osteoporosis (Fig. 3).

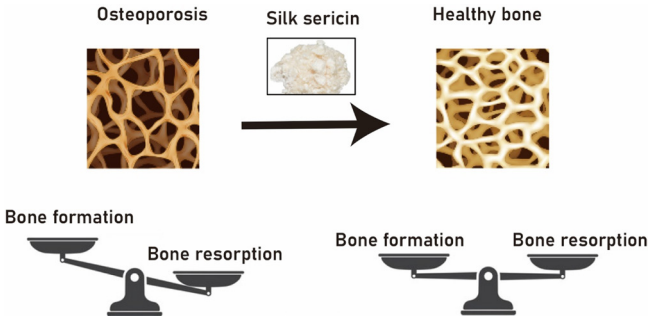

Fig. 3. The benefit of silk sericin-based functional food on the osteoporosis.

Challenges and Barriers

One of the primary challenges facing the adoption of insect-based functional foods is the regulatory and legal landscape. Regulations regarding the production, processing, and sale of edible insects vary widely across different countries. In some regions, edible insects are well-regulated and integrated into the food industry, while in others, they are either unregulated or outright prohibited. Harmonizing regulations at an international level is crucial to facilitate the global trade and acceptance of insect-based foods. Clear guidelines and standards are needed to ensure safety, quality, and consistency in the production and distribution of these foods.

Food safety is a significant concern when it comes to insect-based functional foods (Lisboa *et al.*, 2024). Ensuring that edible insects are free from contaminants, pathogens, and harmful substances is essential for consumer safety. The production and processing of insects must adhere to stringent food safety regulations to prevent risks such as microbial contamination, pesticide residues, and heavy metals. Establishing comprehensive safety protocols and conducting rigorous testing are necessary to build consumer confidence and ensure the safety of insect-based products.

Consumer perceptions and acceptance are critical factors influencing the success of insect-based functional foods (Laureati

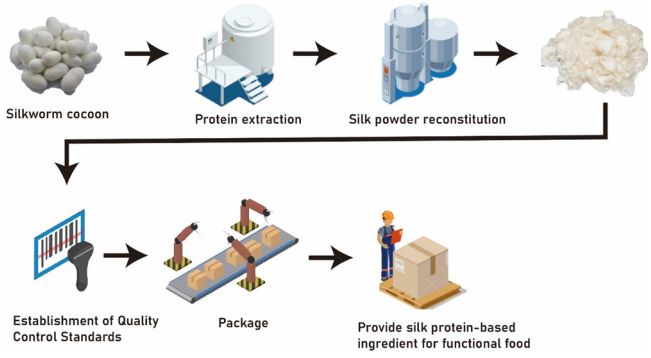

Fig. 4. Processing for silk sericin-based functional food.

et al., 2024). Many consumers may be hesitant or resistant to the idea of eating insects due to unfamiliarity, disgust, or concerns about taste and texture (Orkusz and Orkusz, 2024). Effective marketing strategies, product innovation, and educational initiatives are needed to shift consumer perceptions and increase acceptance. Highlighting the nutritional benefits, environmental sustainability, and culinary potential of insect-based foods can help overcome resistance and foster a positive attitude towards these products.

Potential allergenicity is another significant barrier to the widespread adoption of insect-based functional foods (Lisboa *et al*., 2024). Some individuals may be allergic to certain proteins found in insects, like allergies to shellfish or other arthropods. Identifying and labeling potential allergens is crucial to prevent allergic reactions and ensure consumer safety. Research into the allergenic potential of different insect species and the development of appropriate testing and labeling protocols are essential steps in addressing this challenge.

Standardization and quality control are vital for ensuring the consistency and reliability of insect-based functional foods (Fig. 4). Variability in the nutritional composition, safety, and quality of insect products can pose significant challenges. Developing standardized methods for farming, processing, and testing edible insects is necessary to ensure uniformity and quality across the industry. Implementing robust quality control measures and establishing industry-wide standards can help maintain the integrity and reputation of insect-based foods.

Conclusion

Insect-based functional foods represent a promising avenue for addressing both nutritional and environmental challenges. Their high content of quality protein, healthy fats, essential vitamins, and minerals positions them as a viable alternative to traditional animal-based protein sources. Moreover, the bioactive compounds found in insects can contribute significantly to weight management, cardiovascular health, anti-inflammatory effects, gut health, and potentially cancer prevention.

Despite the promising benefits, several challenges must be addressed to facilitate the widespread adoption of insect-based functional foods. Regulatory and legal barriers, food safety concerns, consumer acceptance, potential allergenicity, and the need for standardization and quality control are critical issues that require comprehensive strategies. Harmonizing international regulations, conducting rigorous safety testing, and implementing effective marketing and educational initiatives will be crucial in overcoming these barriers.

In conclusion, insect-based functional foods offer significant potential for enhancing health and sustainability. As the global population seeks more efficient and nutritious food sources, the integration of edible insects into the functional food market presents an innovative solution. Continued research and collaborative efforts across various sectors will be essential to realize the full potential of insects as a sustainable and health-promoting component of the global food system.

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