International Journal of Pharmacy and Pharmaceutical Science 2025; 7(2): 791-804

International Journal of Pharmacy and Pharmaceutical Science

ISSN Print: 2664-7222
ISSN Online: 2664-7230
IJPPS 2025; 7(2): 791-804
www.pharmacyjournal.org
Received: 12-10-2025
Accepted: 15-11-2025

Manjula M Venkatappa
Department of Food Science and Nutrition, Tumkur University, Tumkur, Karnataka, India

Keerthana Prakash
Department of Food Science and Nutrition, Tumkur University, Tumkur, Karnataka, India

Chandana Giriraj
Department of Food Science and Nutrition, Tumkur University, Tumkur, Karnataka, India

Devaraja Sannaningaiah
[1)] Department of Food Science and Nutrition, Tumkur University, Tumkur, Karnataka, India
[2)] Departments of Studies and Research in Biochemistry, Tumkur University, Tumkur, Karnataka, India

Corresponding Author:
Devaraja Sannaningaiah
[1)] Department of Food Science and Nutrition, Tumkur University, Tumkur, Karnataka, India
[2)] Departments of Studies and Research in Biochemistry, Tumkur University, Tumkur, Karnataka, India

Edible insects as future foods: Nutritional, Environmental sustainability and Challenges

Manjula M Venkatappa, Keerthana Prakash, Chandana Giriraj and Devaraja Sannaningaiah

DOI: https://www.doi.org/10.33545/26647222.2025.v7.i2i.277

Abstract
Entomophagy, or eating insects, is increasingly gaining attention around the world because of its nutritional benefits and its potential to support environmental and economic sustainability. As the global population continues to grow, finding ways to produce food without harming the planet has become a major challenge. Edible insects are now seen as a promising solution to this issue. They offer an impressive nutritional profile, containing high-quality protein, healthy fats, vitamins, minerals, and dietary fibre making them valuable in meeting nutritional needs. Beyond their nutritional value, insects are efficient to raise. They require less food, less space, and less water compared to traditional livestock. They can also be fed using agricultural by-products and food waste, making them useful in recycling resources and reducing environmental impact. Compared with cattle and other livestock, insect farming produces far fewer greenhouse gases and ammonia while still offering equal or even superior nutritional quality. Although insects have been eaten for centuries in many tropical and subtropical regions, their acceptance in Western countries is relatively new. However, interest is growing rapidly, both in academic research and commercial product development. Today, insects are being explored not only as food for humans but also as an alternative protein source for fish farming, poultry feed, pigs, and even pets. As this field continues to grow, more attention is being given to developing insect-based food technologies, improving processing methods, and understanding consumer attitudes. This review explores the nutritional value of edible insects, their environmental benefits, current and emerging applications, and the key challenges related to public acceptance and large-scale adoption.

Keywords: Edible insects, nutritional content, pharmacology, sustainability, challenges

Introduction
Insects are now being recognized as an excellent source of high-quality protein, and more people around the world are beginning to include them in their diets. Many researchers and food developers are exploring the possibility of using insects as an alternative protein source for animals and even humans. While eating insects has been a long-standing practice in many tropical countries [1], the idea has only recently gained attention in Western regions. Beyond human consumption, insects are also becoming popular as feed for fish, poultry, pigs, and household pets. The growing number of scientific studies on edible insects shows how quickly this field is expanding. In many tropical areas, edible insects are still collected directly from the wild. They support food security by providing a reliable food source, and when sold, they also help generate income for families [2]. In addition to being harvested from nature, insects can be farmed in controlled environments. Western countries are now exploring this farming approach because the global demand for protein-rich foods continues to rise while land available for raising livestock remains limited. The search for alternative proteins is also driven by the environmental impacts of traditional livestock farming. Raising cattle, poultry, and pigs contributes to several ecological problems, including deforestation, soil degradation, desertification, loss of biodiversity, ammonia pollution, climate change, and water contamination [3]. As a result, interest in insect-based foods continues to grow. Today, products such as freeze-dried insects, insect flour, snacks, pasta, protein bars, burgers, and baked goods made from insects can already be found in parts of North America and Europe. Insects are not only versatile but also highly nutritious, offering both essential fats and proteins along with valuable micronutrients [4].

Since 2003, the Food and Agriculture Organization (FAO) has been actively promoting the nutritional value of edible insects and encouraging their use as both food and animal feed. In recent years, the number of insect farming start-ups has grown around the world, producing various insect species for livestock feed and direct human consumption. In Europe, edible insects are classified as novel foods, meaning companies must complete a formal authorization process before launching insect-based products on the market [5]. The nutritional content of insects varies by species, but many provide high levels of essential nutrients. While their protein digestibility is generally lower than that of conventional animal proteins, it is still higher than many plant-based sources. Insects also supply valuable micronutrients, including riboflavin, folic acid, biotin, and pantothenic acid. Interest in insect-based foods has increased rapidly, fueled by social media, public curiosity, and growing involvement from chefs, food innovators, and entrepreneurs especially in North America and Europe [6]. Globally, more than 1,900 insect species are recognized as edible, and many play an important role in supporting food security in local communities. However, scaling up production remains challenging. The scattered availability of edible insect species, limited plant-based feed sources, and restricted trade opportunities have made wild harvesting common, though indoor farming systems are now emerging as a more reliable and commercial alternative. Traditional knowledge from Indigenous communities can also support scientific research by filling knowledge gaps and improving farming practices [7]. Today, insect-based ingredients appear in a variety of foods from everyday dishes to innovative meat and fish substitutes. In Finland, for example, species such as house crickets, European honeybees, migratory locusts, yellow mealworms, lesser mealworms, and black soldier flies are legally approved for consumption. Common substrates used in insect farming include soybean meal and poultry feed, although researchers are increasingly exploring the use of agricultural by-products and industrial side streams to develop more sustainable and cost-effective farming systems [8]. Pustular components can be found in a variety of foods, including familiar dishes made with meat and fish. In Finland, current regulations now permit the consumption of several insect species, including house crickets, European honeybees, migratory locusts, yellow mealworms, lesser mealworms, and black soldier flies. Soybean meal and poultry feed are among the most commonly used substrates for raising edible insects, although researchers are increasingly exploring alternative raw materials such as agricultural by-products and industrial side streams as potential feed sources [9]. Once safety evaluations are completed, the European Commission will make final decisions on approving insect-based foods as part of the novel food category. Although scientific research into edible insects is relatively recent, growing innovation has shifted the focus from harvesting wild insects in tropical regions to developing systematic insect farming operations worldwide [10]. Currently, most insect-derived products are used in animal feed, particularly for pets, but their use in aquaculture is predicted to expand significantly in the coming years. The choice of insect species for farming depends on several factors, including suitability for automation, access to low-cost feed substrates, resilience against disease, and commercial viability. Beyond nutrition, insects offer multiple benefits-including health-supporting bioactive compounds and they continue to drive the development of new processing and production methods. The insect industry is expanding rapidly, supported by increasing collaboration among producers, researchers, regulatory bodies, and the general public [11]. Table 1 represents the Nutritional composition of edible insects.

Table 1: Represents the nutritional composition of edible insects

Species	Crude Protein (%)
Coleoptera	41.75
Blattodea (cockroach)	68.33
Diptera	48.81
Hemiptera	48.83
Hymenoptera	51.43
Lepidoptera	65.25
Orthoptera	59.17
Isoptera (termites)	33.00

Species	Crude Fat (%)
Coleoptera	25.05
Blattodea	35.81
Diptera	21.94
Hemiptera	32.25
Hymenoptera	18.71
Lepidoptera	37.95
Orthoptera	19.92
Isoptera	36.80

Nutritional composition

The nutritional value of edible insects is mainly determined by their protein and fat content, along with the presence of essential amino acids and fatty acids. These components collectively define the overall dietary quality of insect-based foods. Protein levels can vary significantly depending on the species, developmental stage, the type of feed used during rearing, and even the analytical methods applied during testing. Research on twelve commonly consumed insect species has revealed considerable variability in nutrient composition, with standard deviations in some cases exceeding 50% of the average values reported [12]. For instance, the protein content of *Acheta domesticus* (house cricket) ranges from 7.5% to 23.7% on a fresh-weight basis and 5.6% to 15.2% on a dry-weight basis. Its fat content also varies, from 2.4% to 6.7% (fresh weight) and 4.8% to 14.0% (dry weight). Another example, *Tenebrio molitor* (mealworm), contains approximately 11.4% protein. Beyond protein and fat, edible insects also provide valuable minerals such as calcium, magnesium, iron, zinc, and phosphorus. Because of this rich micronutrient profile, insects have been proposed as a promising tool to combat "hidden hunger" and nutrient deficiencies in developing regions (13-14). Most edible insect species contain less than 3% dietary ash, although some caterpillar species (order Lepidoptera) show higher values. In addition, insects are notable sources of vitamins such as riboflavin, biotin, and pantothenic acid. They also contain chitin a structural carbohydrate that typically makes up at least 10% of their dry mass. Chitin is especially valuable in agriculture, where it serves as a natural, non-toxic biopolymer with potential applications in plant growth regulation, tissue repair, and post-harvest preservation of fruits and vegetables by minimizing moisture loss during storage. Although the global demand for edible insects and insect-based products is steadily increasing, concerns regarding their safety still persist. One of the primary risks involves microbial contamination. In some studies, harmful bacteria and moulds have been detected in caterpillar samples and other wild-harvested insects [15]. There are also toxicological risks, which may come from naturally occurring insect compounds such as the monoterpene cantharidin, or from environmental contaminants that insects may absorb during their life cycle. Exposure to such toxins has been associated with symptoms including nausea and vomiting. Additionally, cases of parasitic infections, botulism, and other food-borne illnesses linked to insect consumption have been reported. These concerns are especially relevant for insects collected from the wild, where farming conditions and hygiene cannot be controlled. Despite these challenges, insects continue to be recognized for their nutritional and functional value. They are rich in chitin, vitamins, minerals, and other bioactive compounds, making them beneficial not only as food but also for use in various industrial applications. The nutritional composition of widely consumed edible insect species including the house cricket (*Acheta domesticus*), black soldier fly (*Hermetia illucens*), and yellow mealworm (*Tenebrio molitor* L.) is explained as follows.

House Cricket (*Acheta domesticus*)

The house cricket (*Acheta domesticus*), native to regions of Southwestern Asia, is rapidly gaining popularity as a commercially farmed edible insect. It is well regarded for its high protein content, favourable amino acid profile, and diverse range of essential nutrients. Due to its strong nutritional value and minimal ecological footprint, A. domesticus is increasingly viewed as a promising sustainable protein source for the food industry. Its safety, ease of farming, and efficient feed conversion further enhance its potential as an environmentally responsible alternative to conventional animal proteins [16]. Table 2 represents the classification of *Acheta domesticus* insects.

Table 2: Represents the classification of *Acheta domesticus* insects

Rank	Classification
Domain	Eukaryota
Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Orthoptera
Suborder	Ensifera
Family	Gryllidae
Genus	Acheta
Species	*A. domesticus*

Nutritional composition of house cricket

Crickets can be raised on a variety of substrates, each producing different protein and fat levels. In the present study, the crude protein content of the substrates fed to house crickets ranged from 6.3% to 22.9%, while the protein content of the crickets themselves varied from 48.1% to 76.2% on a dry-matter basis. Although high-protein substrates may help increase the protein content of crickets, other factors such as vitamin and mineral composition, as well as the overall formulation of the feed also play important roles. The study further showed that final-instar crickets fed a commercial high-protein substrate (22% protein; Pure Pride cricket feed) achieved significantly greater growth, with body weights and body lengths averaging 9% higher than those of crickets fed a lower-protein substrate (16% protein; Betagro chicken feed) [17].

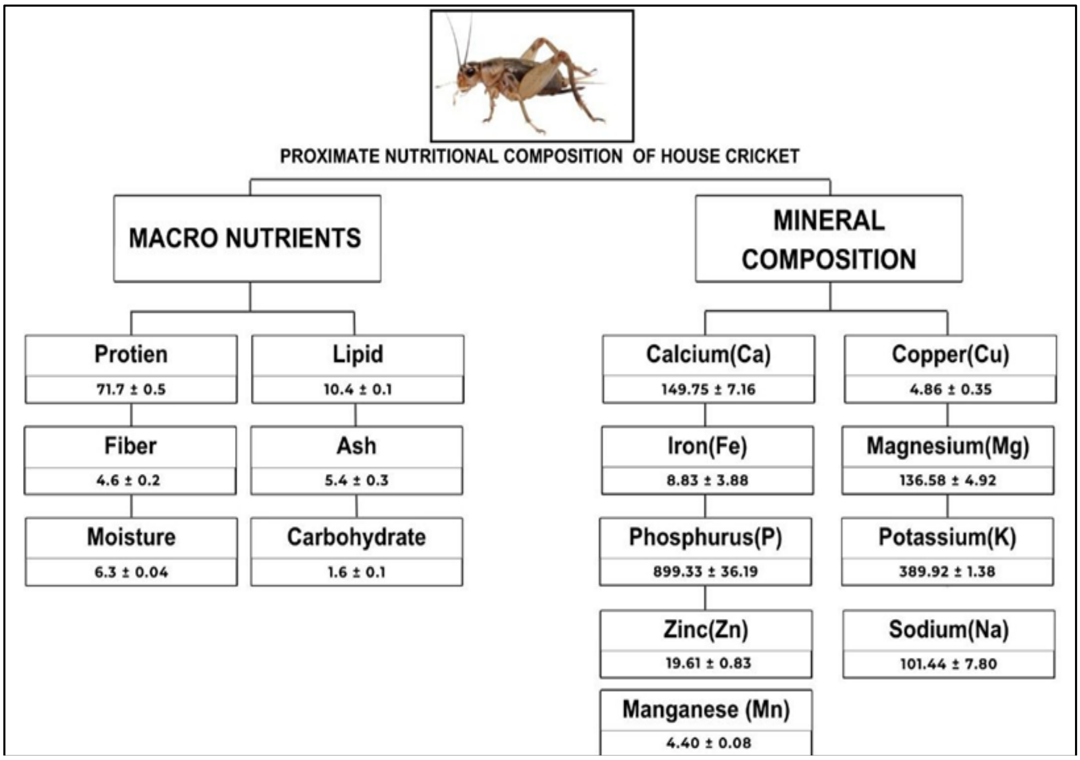

Fig 1: Nutritional composition of house cricket

Pharmacological properties of house cricket

Anti-tyrosinase activity

Bioactive compound analysis confirmed the presence of alkaloids, saponins, steroids, phenolics, and flavonoids across all crude cricket extracts. Among the tested solvents, the methanol extract contained the highest concentration of phenolic compounds. Notably, the extract from the short-tailed cricket previously recognized for its strong anti-tyrosinase activity also exhibited higher levels of α-linolenic acid compared to the other samples. The IC_{50} values associated with anti-tyrosinase activity appear to correlate with the fatty acid composition of the extracts. Saturated fatty acids, including palmitic and stearic acids, did not demonstrate inhibitory effects on tyrosinase. In contrast, unsaturated fatty acids such as oleic, linoleic, and α-linolenic acids have been reported to suppress tyrosinase activity by facilitating enzyme degradation. These findings suggest that unsaturated fatty acids may contribute significantly to the bioactivity observed in cricket extracts [18].

Anti-melanogenesis activity: Extracts from the domestic house cricket did not exhibit tyrosinase inhibitory activity, which may be attributed to their relatively high levels of saturated fatty acids, particularly palmitic and stearic acids. Previous research has demonstrated that effective tyrosinase inhibitors such as heteroaryl coumarins, benzylidene-linked thiohydantoin, and kojic acid-linked thio-quinazoline derivatives can reduce melanin content and exert strong anti-melanogenesis effects. Despite the lack of detectable inhibition in this study, the presence of other bioactive compounds suggests that cricket extracts may still hold potential for influencing melanin synthesis [19] (Figure 2).

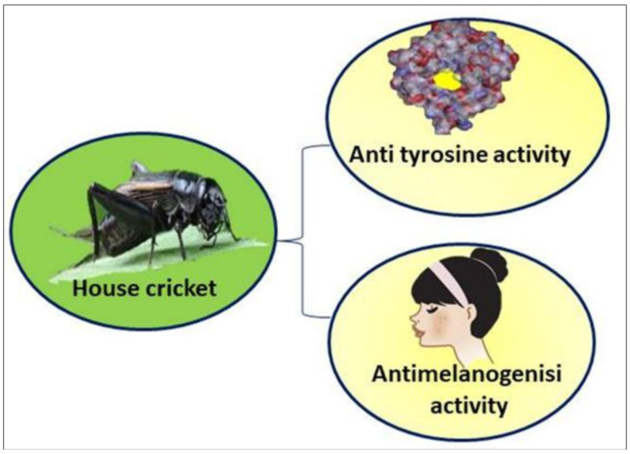

Fig 2: Pharmacological properties of House cricket

Black Soldier Fly (*Hermetia illucens*)

Hermetia illucens, commonly known as the black soldier fly (BSF), is a globally distributed insect belonging to the family Stratiomyidae. Over the past few decades, it has gained growing attention because of its impressive ability to convert organic waste into valuable biomass, making it an important species in sustainable agriculture and animal feed production [20].Adult black soldier flies are typically about 16 mm long, making them medium-sized insects. Their bodies are mostly black, sometimes showing subtle metallic blue or green iridescence on the thorax, and some individuals may also have a faint reddish tint near the end of the abdomen. A distinctive feature is the partially transparent second abdominal segment, which influenced the species' scientific name. The head of the fly is broad with large, well-developed compound eyes, and its antennae are notably long about twice the length of the head. Their legs are black with lighter-colored tarsi, and the wings are thin and membranous. When not flying, the wings rest flat against the body, overlapping neatly along the abdomen [21].

Table 3: Represents the classification of *Hermetia illucens* insects

Rank	Classification
Domain	Eukaryota
Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Diptera
Family	Stratiomyidae
Subfamily	Hermetia
Genus	Hermetia
Species	*H. illucens*

Nutritional composition of Black Soldier Fly (BSF)

Black Soldier Flies (BSF) are remarkably flexible insects that can thrive on many different types of organic waste generated by the agri-food industry. Their growth and development depend heavily on the nutritional value of the material they feed on. For example, substrates rich in easily digestible carbohydrates help the larvae grow more quickly and reach the prepupal stage sooner, often resulting in larger body size [22]. The balance of nutrients in the larvae especially the ratio of protein to fat is closely tied to the nutritional makeup of their diet [23]. When BSF larvae are reared on well-balanced or nutritionally rich feed, they typically develop higher levels of crude protein and fat. Research indicates that a dietary ratio of approximately 2:1:2 for protein, fat, and digestible carbohydrates provides optimal growth conditions in certain studies, such as those conducted during Ramadan fasting periods [24]. While the larval nutritional profile can shift depending on the diet, the extent of the change is usually moderate, as each feed source has its own inherent nutrient composition. Overall, BSF larvae demonstrate strong adaptability, making them an efficient tool for upcycling food waste into valuable protein. Surprisingly, providing the larvae with a protein-rich diet does not always result in the highest protein levels within the insects themselves. This pattern is also seen with minerals such as calcium. In other words, simply increasing dietary protein or minerals does not guarantee that the larvae will store these nutrients in the same proportion. The nutritional makeup of the substrate including its protein, fat, minerals, amino acids, and fibre plays a direct role in shaping the nutrient profile of the black soldier fly larvae. However, the relationship is not always linear. Even when fed high-protein substrates, the larvae do not always reach their highest possible protein values (Figure 3).

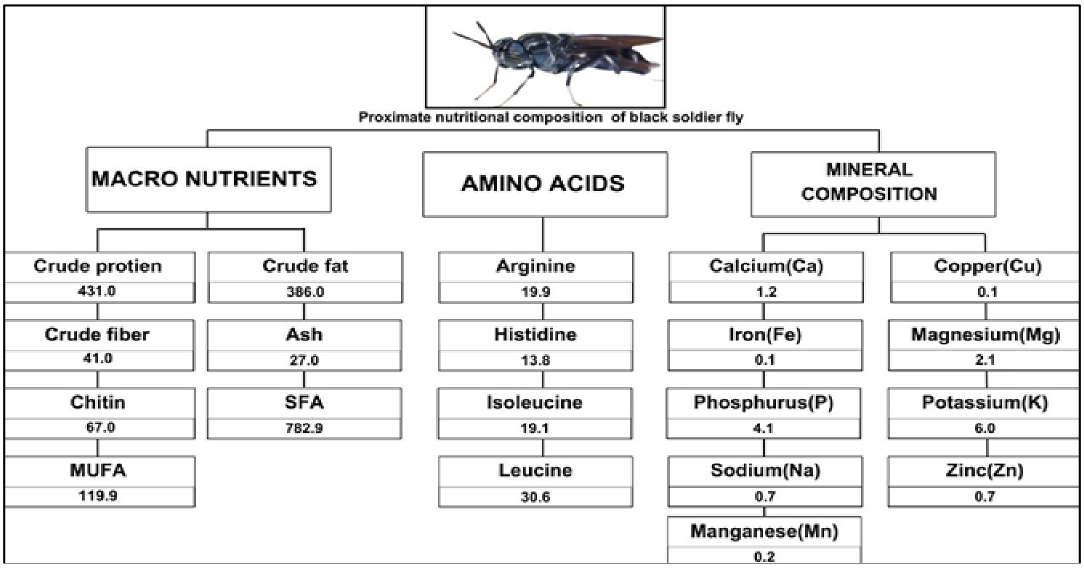

Fig 3: Nutritional composition of black soldier fly

Pharmacological Properties of the Black Soldier Fly

The black soldier fly (*Hermetia illucens*) possesses several valuable pharmacological properties, including antimicrobial, anti-inflammatory, and antioxidant activities. Because of these characteristics, BSF-derived compounds are increasingly being explored as potential ingredients in cosmetics, pharmaceuticals, and food products [25] (Fige 4).

Antimicrobial Activity

Black soldier fly (BSF) larvae naturally produce several antimicrobial peptides (AMPs), including defensins, cecropins, and attacins. These compounds help protect the larvae from harmful microbes and have strong antibacterial and antifungal properties. Research has shown that these peptides are effective against a wide range of pathogens, including both Gram-positive and Gram-negative bacteria such as *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, and *Salmonella species*. Because of their strong antimicrobial activity, BSF-derived peptides are increasingly being explored as potential natural alternatives to conventional antibiotics. This makes them highly promising for future applications in medicine, livestock production, and food safety [26].

Anti-inflammatory Activity

Proteins and bioactive peptides found in BSF larvae have also shown promising anti-inflammatory properties. They work by helping regulate the production of cytokines the molecules responsible for triggering and controlling inflammation in the body. Because of this effect, BSF-derived compounds are being explored as potential natural treatments for chronic inflammatory disorders, including conditions like arthritis and inflammatory bowel disease. Although research is still ongoing, these findings suggest that BSF larvae may offer more than just nutritional benefits they may also contribute to future biomedical and therapeutic applications [27].

Antioxidant Activity

Black soldier fly (BSF) larvae contain several beneficial compounds such as phenolics, flavonoids, and chitin that have strong antioxidant properties. These natural antioxidants help neutralize harmful free radicals in the body, reducing oxidative stress. Lower oxidative stress is associated with better protection against cellular damage, which plays an important role in slowing aging and lowering the risk of diseases such as cardiovascular disorders and neurodegenerative conditions. Because of this, BSF-based ingredients are now being explored for potential use in functional foods and health supplements [28].

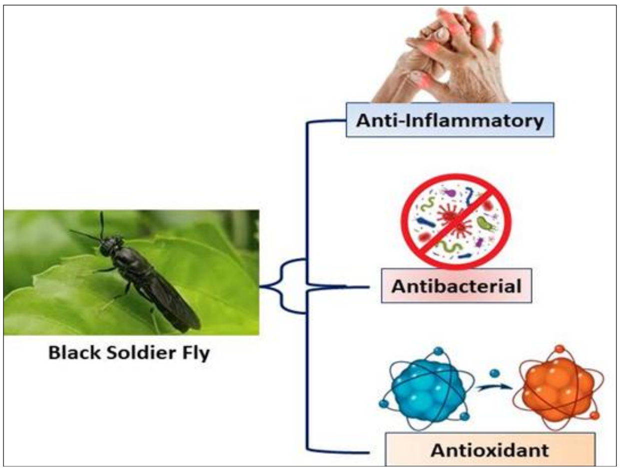

Fig 4: Pharmacological properties of black soldier fly

Yellow Mealworm also known as *Tenebrio molitor* L

Mealworms are the larval stage of the yellow mealworm beetle, *Tenebrio molitor*, a member of the darkling beetle family. These insects thrive in warm, humid environments. During mating, male beetles release chemical signals called sex pheromones to attract females [29].Beyond their role in nature, *T. molitor* has gained importance in research and food science. They are commonly used in biomedical studies and are increasingly recognized as a nutritious food source for both humans and animals. However, in some situations especially storage facilities they are also considered pests because they can infest grain-based products. Like many insects, *T. molitor* undergoes complete metamorphosis with four life stages: egg, larva, pupa, and adult. The worm-like larvae typically grow to about 2.5 cm (0.98 in), though some may reach up to 3.2 cm (1.25 in). The adult beetles are smaller, generally measuring 1.25 to 1.9 cm (0.49-0.75 in), and are dark brown to black in color [30].These beetles can be identified by several unique features. Their bodies have straight, evenly spaced grooves, and unlike many similarly sized ground beetles which generally have five segments in their hind tarsi *T. molitor* adults have only four [31]. Table 4 presents the classification of *Tenebrio molitor* L.

Table 4: Represents the classification of *Tenebrio molitor* L insects

Rank	Classification
Domain	Eukaryota
Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Coleoptera
Suborder	Polyphaga
Family	Tenebrionidae
Genus	Tenebrio
Species	*T. molitor*

Nutritional composition of yellow mealworm

The nutritional value of yellow mealworms largely depends on the type of feed they consume. Among the different diets tested, Brewer's Spent Grains (BSG) have been shown to produce larvae with higher levels of crude protein and carbohydrates compared to feeds like bread or cookies. BSG also enhances food digestion and taste better than wheat bran (WB). One key distinction between BSG and WB is their fat content: BSG contains less fat but more fibre. When mealworms are raised on diets with varying protein-to-fat ratios, those fed high-protein diets whether high in fibre or low in fibre generally show the greatest protein content. However, their fat levels tend to shift depending on the specific feed provided. In a study carried out by Alves using bocaiuva pulp flour as a feed source, diets rich in lipids helped balance the protein and fibre content of the larvae and ultimately improved their nutritional profile [32] (Figure 5).

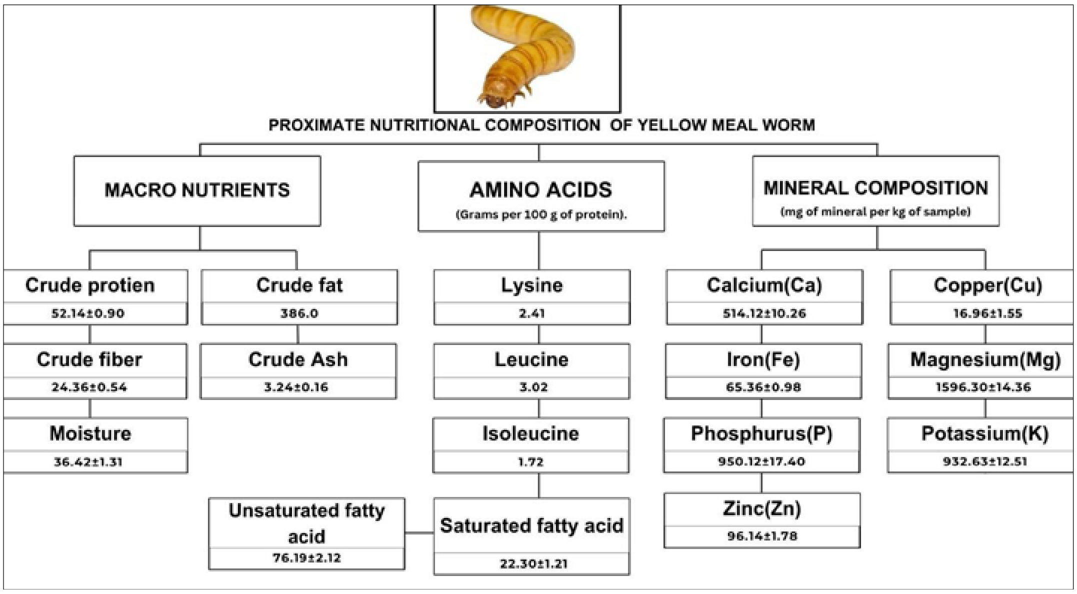

Fig 5: Nutritional composition of yellow mealworm

Pharmacological properties of Yellow Mealworm:

Mealworms aren't just a source of nutrition they also contain several beneficial bioactive compounds that may support human health. Research shows they have antioxidant, anti-diabetic, anti-inflammatory, and anti-hypertensive properties, making them more than simply a protein-rich food source [33]. In addition to these health-promoting effects, mealworms contain a diverse range of fatty acids. These include beneficial unsaturated fats, such as oleic acid and linoleic acid, which are commonly found in heart-healthy foods, as well as saturated fats like palmitic acid. Together, these components contribute to the growing interest in mealworms as a sustainable and functional food ingredient (Figure 6).

Antimicrobial Activity

Yellow mealworms contain natural bioactive peptides and antimicrobial compounds that can fight harmful microorganisms. Research has shown that these substances are effective against several well-known pathogens, including *Staphylococcus aureus*, *Escherichia coli*, *Salmonella species*, and the fungus Candida albicans. Because of these strong antibacterial and antifungal effects, yellow mealworms are gaining attention as a potential natural alternative to traditional antibiotics. This makes them especially interesting for future applications in medicine, food preservation, and functional foods [34].

Anti-inflammatory Activity

Proteins and lipids extracted from yellow mealworms have also been found to support healthy immune responses. These compounds help balance inflammation in the body by lowering pro-inflammatory markers like TNF-α and IL-6, while increasing the production of anti-inflammatory cytokines. Because of this regulatory effect, mealworm-based extracts may hold therapeutic potential for conditions linked to chronic inflammation, such as arthritis and inflammatory bowel disease. Their ability to naturally moderate inflammatory pathways makes them a promising target for future research in functional foods and medical nutrition [35].

Antioxidant Properties

Yellow mealworms contain flavonoids, polyphenols, and essential fatty acids that contribute to their antioxidant activity. These compounds neutralize reactive oxygen species (ROS), reduce oxidative stress, and may help prevent conditions associated with aging, cardiovascular diseases, and neurodegenerative disorders.

Anti-hypertensive Activity

Yellow mealworms are also a natural source of omega-3 and omega-6 fatty acids nutrients that play an important role in heart and metabolic health. These healthy fats help regulate blood cholesterol levels and may lower the risk of conditions such as atherosclerosis. Because of this, mealworm-based ingredients could be especially beneficial for individuals looking to support cardiovascular function or manage metabolic disorders [36].

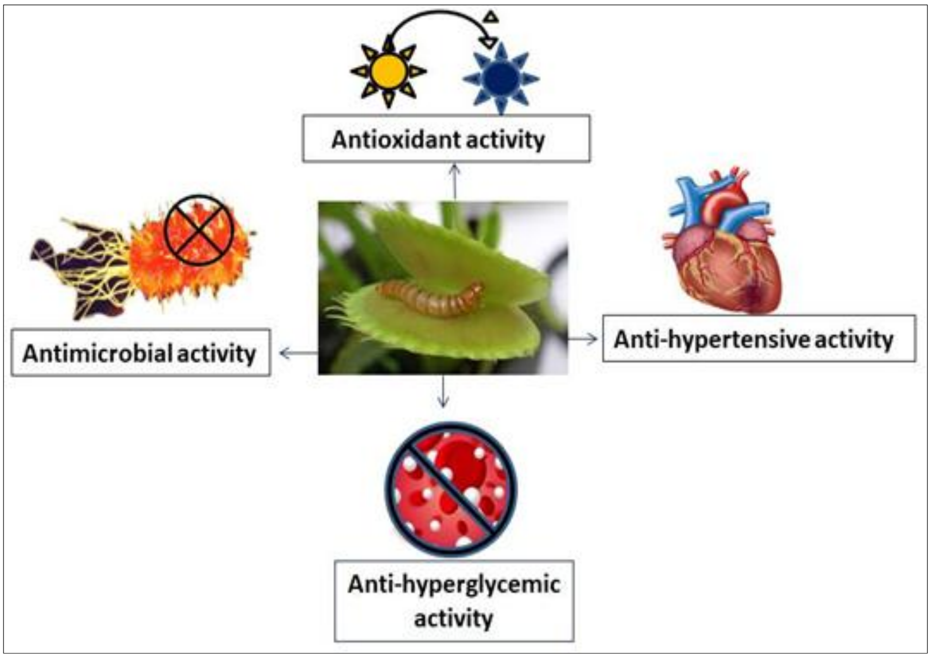

Fig 6: Pharmacological properties of yellow mealworm

Sustainability and Environmental Impact

This section examines how insect farming compares to traditional livestock production in terms of environmental impact. Key sustainability factors such as energy consumption, Greenhouse Gas Emissions (GHGs), water and land use, and feed-to-protein efficiency are analyzed to evaluate whether insects can serve as a viable protein alternative. Since many edible insect species can thrive on low-value organic waste streams, they have the potential to transform food by-products into high-quality protein. By comparing insects with conventional livestock systems, this section explores whether insects could replace or supplement existing protein sources like fishmeal in animal feed, offering a more sustainable and resource-efficient solution for the future [37].

Global Warming and Dietary Shifts

In December 2015, leaders from 195 countries gathered in Paris for the United Nations Climate Conference and signed the first global, legally binding Climate Agreement. The goal was ambitious but essential: keep global warming well below 2 °C. One of the major targets highlighted in the agreement was the livestock industry, which is responsible for a large share of global greenhouse gas emissions roughly 64-78% of emissions from agriculture alone. Because of this significant environmental footprint, reducing emissions from livestock farming is considered one of the most impactful strategies for climate mitigation within the land-use, agriculture, and forestry sectors [38].

Key mitigation strategies include

Reducing greenhouse gas emissions from livestock farming can happen in several ways. One approach is to lower emissions that come from manure. Another effective strategy is reducing how much livestock-based food people consume, which slows down demand for large-scale animal farming. Improving carbon storage in grazing lands can also help minimize environmental impact. Research shows that changing dietary habits could make a big difference. For example, in the European Union, transportation-related emissions could drop by 25-40%, and in the United Kingdom by up to 65%, if people reduced their consumption of meat, especially beef and lamb. This is because producing meat from ruminant animals uses far more land sometimes 50 times more than growing vegetables. Cutting the intake of red meat and fatty animal products by even half could meaningfully reduce greenhouse gas emissions. Another way to make food systems more sustainable is by reducing the use of feed derived from animals in aquaculture, poultry, and pig farming. This shift would not only decrease emissions but also help protect ecosystems and biodiversity [39].

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is used to evaluate the environmental impact of a product across its entire lifespan from production to disposal. Studies show that insect farming generally produces far fewer emissions of CO_2, CH_4, N_2O, and NH_3 compared to conventional livestock systems such as cattle. However, the exact environmental impact varies depending on the insect species and the farming system used. Existing LCA research has focused primarily on black soldier fly larvae, housefly larvae, mealworms, and house crickets. Since insects are poikilothermic (cold-blooded), they rely on external heat sources to maintain body temperature. As a result, energy use for heating can be higher in insect farms than in traditional livestock production. Even so, insects make up for this through their high feed conversion efficiency, meaning they convert feed into body mass much more effectively than cattle, pigs, or poultry [40]. In traditional livestock farming, feed production contributes the most to environmental impact. Insects offer a promising environmentally friendly alternative because: They can grow on low-value organic side streams and food waste, they use significantly less land and water and their feed conversion rates are substantially higher than conventional livestock. Despite these advantages, comparing insects to traditional protein sources remains complicated. For example, soybean meal requires less energy to produce but demands large areas of land and contributes to deforestation. Fish meal, on the other hand, has high energy costs and notable greenhouse gas emissions. When deforestation related to soybean production is factored in, the environmental cost becomes equal to or even greater than-that of fish meal. Ultimately, the sustainability of insect-based feeds depends largely on the substrate used to rear the insects. Some low-value streams, such as sugar beet residue from Vermont, demonstrate minimal environmental impacts. Others, like beetroot pulp, result in increased impacts due to their lower suitability for larval growth [42].

Ecosystems, Biodiversity and Sustainable Harvesting

Across the world, people consume nearly 2,100 species of insects, most of which are found in tropical regions like forests, river systems, and agricultural landscapes. However, as insect consumption grows, issues such as overharvesting and habitat loss are putting pressure on certain species, giving the practice a noticeable human-driven (anthropogenic) impact. For example: In Australia, traditional edible insects like wood grubs and honey ants are becoming harder to find as tourism increases and harvesting intensifies. In parts of Africa, some edible caterpillar species are declining due to unsustainable harvesting and environmental degradation. Aquatic insects are also at risk, mainly from pollution and agricultural runoff affecting freshwater systems. Among all edible insect species, the black soldier fly (*Hermetia illucens*) stands out. Its larvae can convert organic waste including food scraps into valuable protein, reduce harmful bacterial loads, and even serve as a source for biodiesel and other biofuels. Other fly families are also promising for similar applications, such as Muscidae, Stratiomyidae, Calliphoridae, Sarcophagidae, Syrphidae. However, what insects can be fed depends heavily on regulations. For instance, in the European Union, substrates like manure and catering waste cannot legally be used as insect feed. This means that food safety and feed regulations are essential considerations when selecting substrates for insect farming [43].

Environmental risks of insect farming

Insect farming does offer environmental benefits, but it also comes with risks that affect people, animals, plants, and entire ecosystems. Because of this, countries need to carefully evaluate which insect species can be farmed and determine whether they fall under quarantine pest regulations outlined by the International Plant Protection Convention (IPPC). To prevent harmful species from entering new ecosystems, imports of insects and insect-based products are closely monitored by nine Regional Plant Protection Organizations (RPPOs). If a species is considered invasive or poses risks to health or the environment, it may be banned from use. To ensure safety, national plant protection services and food authorities conduct risk assessments before insects are approved for farming or food production. Maintaining strict containment is important because, just like other domesticated animals, farmed insects can become pests if they escape into the environment. As global interest in edible insects continues to grow, pressure on wild insect populations is increasing especially in tropical regions where most harvesting still takes place. This could threaten both biodiversity and long-term ecological balance. Other environmental challenges include pesticide exposure, pollution, and habitat changes. Large-scale insect farming will also require feed, energy, and infrastructure, meaning it is not impact-free. While insect protein is often labelled as a sustainable alternative, scaling up production will demand careful planning and responsible management. Finally, because some insects can carry pathogens or behave like pests, food safety concerns must be considered when bringing insects into mainstream food and feed systems. Responsible regulation, monitoring, and farming practices are essential to ensure insects truly become a sustainable resource rather than a new environmental problem [44].

Advances in processing, product development, and application

As global demand for animal protein continues to rise, edible insects are gaining attention as a sustainable and nutritious alternative. Many insect species are packed with high-quality protein, healthy fats, chitin, and even offer a beneficial balance of omega-3 and omega-6 fatty acids. Despite these advantages, cultural hesitation and limited large-scale production strategiesvespecially in Western countries still pose barriers to wider acceptance. To overcome these challenges, researchers and industry experts have experimented with multiple processing techniques to make insect-based foods safer, longer-lasting, and more appealing. Methods such as sun-drying, oven- and microwave-drying, freeze-drying, fermentation, marination, freezing, and dry fractionation have all been explored. In addition, manufacturers have created a range of products that hide the insect origin such as insect-fortified chocolate, biscuits, and even ground-beef substitutes to make them more acceptable to consumers. Interestingly, younger individuals, particularly in parts of Europe, are showing greater openness toward trying insect-based foods. This emerging interest suggests that targeting receptive consumer groups could accelerate mainstream acceptance. Moving forward, innovation in insect farming, processing, and storage will need to focus on sustainability, product convenience, flavor, and reducing psychological barriers such as disgust or unfamiliarity. These improvements will be essential for bringing insect-based foods into everyday diets and strengthening their role in the future food system [45]. Table 5 summarises the major applications of insects.

Table 5: Summarises the major applications of insects

Insect Name	Product	Applications
General Edible Insects	Powder, Paste	Ingredients in various foods, nutritional supplements
General Edible Insects	Whole Insects	Traditional dishes, snacks
Crickets, Grasshoppers, Mealworms	Rearing in family-run enterprises	Primarily pet food, potential human food production
Housefly larvae, silkworms, yellow mealworms, black soldier flies	Insect-based food for industrial production	Potential for large-scale commercial production
Mealworms	Flour, Protein Isolates, Oil	Baked goods, pasta, meat alternatives, dietary supplements, cosmetics
Crickets	Protein Powder, Flour, Roasted	Protein bars, shakes, snacks, baked goods, ingredient in processed meats, pet food
Black Soldier Fly Larvae	Protein Meal, Oil, Chitin	Animal feed, aquaculture feed, biodiesel production, bio plastic production, fertilizer for soil amendment
Locusts	Roasted, Flour, Protein powder	Snacks, protein supplements, ingredient in savory dishes, cultural food products
Silkworm Pupae	Canned, Fermented, Oil	Traditional food products, snacks, fermented sauces, functional foods, feed for animals

Processing Technologies

There are many ways to process edible insects before they are used as food or ingredients. Some of the simplest methods include drying and blanching, which help improve safety, texture, and shelf life. More advanced approaches focus on extracting valuable compounds such as proteins, fats, or bioactive substances. Several extraction techniques are used depending on the type of insect and the desired end product. These include chemical extraction, sonication-assisted extraction, and alkaline extraction followed by acid precipitation. Other methods, such as defatting, supercritical CO_2 extraction, dry fractionation, and enzymatic hydrolysis, help separate and refine useful components. Modern technologies including ultrasound-assisted extraction, Soxhlet extraction, water extraction, Folch extraction, and cold atmospheric pressure plasma have also been explored to improve efficiency, purity, and sustainability in insect processing. Together, these techniques allow insects to be transformed from whole raw material into versatile ingredients suitable for use in food, feed, pharmaceuticals, and functional products [46].

Blanching

Blanching is one of the most common pre-treatment techniques used in both small-scale and industrial insect processing. During this process, the insects are briefly boiled and then quickly cooled usually by transferring them into ice water or rinsing them under cold running water to stop the cooking process. This simple step plays a key role in improving food safety: it lowers bacterial contamination and deactivates enzymes that could lead to spoilage, fermentation, or foodborne illness. Because of these benefits, blanching is often considered an essential step before further processing or storage of edible insects [47].

Dehydration

Drying is one of the most widely used ways to preserve food, and the same applies to edible insects. It helps extend shelf life and makes storage and transportation much easier. A variety of techniques can be used from traditional sun-drying and oven-drying to more advanced options like freeze-drying and microwave-assisted drying. Frying and roasting can also serve as drying methods while improving flavor and texture. The main purpose of drying is to remove moisture. When water content is reduced, there's less available for microbial growth, enzyme activity slows down, and spoilage becomes much less likely. Most bacteria cannot grow when the water activity (aw) drops below 0.65, so lowering this value is key to making insects safe and stable for long-term storage [48].

Freeze Drying

Freeze drying is particularly effective for preserving the nutritional characteristics of insects because the process occurs at low temperatures, reducing oxidative and microbiological spoilage. Freeze-dried insects retain high nutritional quality; however, the method is relatively expensive for large-scale industrial use. Oven drying, while more energy-efficient and cost-effective, results in lower lipid oxidation and good protein solubility, making it suitable for both industrial and research applications [49].

Microwave-Assisted Drying

Microwave drying has proven to be an effective method for reducing moisture and microbial activity in *Tenebrio molitor* larvae, often bringing the water activity level below 0.6. Most nutrients remain stable throughout the process, although a noticeable reduction in vitamin B_{12} has been observed. While microwave drying shows strong potential, especially in terms of efficiency, more research is needed. Future studies comparing its sensory characteristics such as texture, aroma, and flavour with other methods like freeze-drying, hot air drying, and vacuum drying will help determine its suitability for both industrial applications and consumer acceptance [50].

Technologies for Extracting Valuable Fractions

Proteins from edible insects can be extracted using several approaches, including water-based methods, organic solvents, and enzymatic hydrolysis. The efficiency of extraction depends on factors such as pH, solvent type, ionic strength, and temperature, meaning that careful control of these conditions can significantly improve both protein yield and functional properties. Studies have shown that extraction using hexane can produce higher yields and improved characteristics including colour, crude ash, crude protein, and carbohydrate levels especially when applied to oilseed cake. In contrast, water-based extractions tend to perform better when functional properties, such as emulsification and foaming ability, are the priority. Research also suggests that adding whey protein or its hydro lysates can further enhance the emulsion and foam stability of cricket protein solutions, demonstrating the potential for combining insect proteins with conventional food ingredients to improve texture and performance [51].

Regulatory, health and safety considerations

For insects to become a widely accepted food source in Western countries, it's crucial that production happens on a safe, industrial scale. Large-scale farming allows strict control over hygiene, quality, and safety something that is much harder to guarantee when insects are collected from the wild. It also helps protect natural ecosystems, since many traditionally harvested species are now becoming harder to find, especially in places like Thailand. Despite growing interest in edible insects, there is still no clear global framework that regulates how they should be farmed, processed, and sold. This lack of guidance has created a catch-22 situation: investors are reluctant to support insect-based food companies without clear laws, and governments are hesitant to write those laws before the industry becomes more established. As a result, growth is slower than its potential. India highlights a striking contradiction: Enormous resources are spent killing insects that eat crops crops that contain only about 14% protein while the insects themselves may contain up to 75% high-quality protein suitable for food or feed. Yet in most developed nations, insects are still viewed legally as pests rather than a nutritional resource. Thailand is often considered a global leader in edible insect production, with more than 20,000 registered farms raising over 200 species, including crickets, grasshoppers, palm weevil larvae, and bamboo caterpillars. This growing industry has boosted income for rural farmers, although regulations have not fully kept pace. In many parts of Asia and Africa, voluntary guidelines from the FAO covering hygiene, contaminants, and labelling are shaping early regulatory frameworks. In the United States, food labeling rules have evolved over the last century. The first major law the Federal Food and Drug Act was introduced after the shocking sanitation issues described in Upton Sinclair's The Jungle. The law aimed to prevent misleading labels and unsafe food practices. Later, in 1990, the Nutrition Labeling and Education Act required standardized nutrition labels on packaged foods. Today, nutrition labels are being updated again to make them clearer and more relevant. This is particularly important for insect-based foods because their nutritional makeup can vary widely depending on species, rearing conditions, and processing methods. Products like protein bars, baked items, shakes, and meat alternatives that include insect ingredients will need clear and accurate labels listing insects both by common and scientific names. In the U.S., edible insects used in dietary supplements must meet regulatory requirements for new dietary ingredients if they were not already sold before October 15, 1994. Manufacturers must provide evidence showing that insects are safe under intended consumption levels, and supplements must follow rules governing form and marketing they cannot be sold as replacements for conventional meals. Safety testing also plays an essential role. Genotoxicity testing is often the first step, helping determine whether an ingredient might damage DNA or increase cancer risk. These established tests can be adapted for insect powders and extracts, making them practical tools for early safety evaluation. Additional short-term toxicity studies including animal testing when necessary help identify any harmful effects before products reach the market [52].

Toxicological hazards of insect-based foods and ingredients

Across the globe, one of the biggest barriers to regulating edible insects is the lack of clarity on which species are truly safe for consumption. Insects can absorb environmental contaminants like pesticides, heavy metals, and toxins, and they may also carry harmful microorganisms. Without unified rules on how insects should be farmed, processed, and prepared, these safety concerns make it difficult to scale the industry regardless of whether insects are commercially raised or collected from the wild. A recent safety assessment by ANSES, the French Agency for Food, Environmental and Occupational Health & Safety, analyzed the potential risks of consuming insects within the European Union. Although current research is still limited, ANSES concluded that the edible insect sector urgently needs specific safety regulations to ensure consumer protection. Their report categorized risks into five main areas: Chemical contaminants, including pesticide residues and heavy metals, Physical hazards, such as hard body parts or foreign particles that could cause injury, Allergens, especially for individuals who are already allergic to shellfish or other arthropods, Microbiological threats, including pathogens like bacteria, viruses, fungi, parasites, and their toxins. Risks linked to farming, processing, and storage, where improper practices may increase contamination. The level of processing plays a key role in determining overall safety. Raw insects carry the highest risk, while whole insects that have been properly cooked are considerably safer. Highly processed products such as defatted flours or powders tend to present the lowest risk, as they undergo steps that reduce microbial load and remove contaminants [53].

Order of Insect	Common Name	Consumption Rate Worldwide by Human Population (%)
Coleoptera	Beetles	31
Lepidoptera	Butterflies, moths	18
Hymenoptera	Bees, wasps, ants	14
Orthoptera	Grasshoppers, locusts, crickets	13
Hemiptera	Cicadas, leafhoppers, planthoppers	10

Consumer acceptability and Socio-cultural perspective

People tend to have very different reactions to insects as food depending on cultural context. In regions where eating insects is a long-standing tradition, insects are valued as an important source of protein, and knowledge about which species are edible is passed down through generations. Here, entomophagy is familiar, culturally rooted, and accepted as a normal part of life. By contrast, in many Western countries, insects are often seen as dirty, dangerous, or disgusting. Popular media reinforces this perception: shows like Fear Factor and I'm A Celebrity…Get me out of here! portray eating insects as a shocking challenge rather than a legitimate food choice. As a result, Western consumers often have a strong psychological barrier against insect consumption. Surveys highlight this reluctance: only around 12.8% of men and 6.3% of women in Western societies say they would consider replacing meat with insects, and only 19% are willing to try insects as a meat substitute at all. Interestingly, demographic factors like age, gender, or income don't seem to predict willingness. Instead, attitudes are shaped by factors such as, Food neophobia-fear of trying new foods, Familiarity-exposure to insects as a food source, Environmental awareness-concern for sustainability, Convenience-ease of incorporating insects into meals. Attachment to meat-based diets-preference for traditional protein sources. People who are more resistant to change, less environmentally motivated, or strongly attached to conventional meat diets are the least likely to try insect-based foods. However, acceptance improves when insects are presented in familiar, convenient forms-like insect flour baked into cookies, bread, or other processed foods. Research from Denmark and Italy shows that providing clear information about the nutritional and environmental benefits of insects can significantly increase willingness to consume them, with effects lasting for at least two weeks. Conversely, misleading information such as claiming a product contains insect flour when it doesn't can reduce perceived flavor, even if no insect ingredient is present. Interestingly, Western consumers are more comfortable with insects as animal feed rather than as direct human food. For example:, About 66% of farmers in Belgium accept insects as feed, Over 80% of consumers want more information about insects in feed, 75% are willing to eat animals that have been fed insect-based diets. This suggests that a practical first step in increasing acceptance of entomophagy may be to integrate insects into animal feed, thereby familiarizing consumers indirectly. Ultimately, attitudes toward insects are strongly influenced by culture and religion, explaining why insect consumption is widespread in some regions and resisted in others. In cultures with a long history of entomophagy, insects are appreciated as nutritious and safe. In many Western societies, insects remain stigmatized as unclean, highlighting the importance of education, exposure, and safe processing to gradually shift public perception [54].

Challenges and Future Directions

In addition to their environmental and nutritional benefits, insects offer significant economic advantages when used as food for humans or livestock. Southeast Asia particularly Thailand provides the clearest example. There, insect farming and trade are well established, with imports of edible insect products alone valued at around 1.14 million USD per year. Many commonly consumed insect species are priced higher than traditional protein sources, making insect farming a stable and profitable livelihood. For example, medium-sized cricket farms producing 500-750 kg of crickets four to five times per year can earn between 4,270 and 9,970 USD annually, in a country where the average national income is about 5,640 USD. In parts of Africa, edible insects also contribute substantially to household incomes. In Namibia, for instance, a 50 kg sack of mopane caterpillars sells for roughly 71 USD and can even serve as a barter item. The global edible insect market is expanding rapidly. In 2015, the combined market value across countries such as the US, Belgium, France, the UK, the Netherlands, China, Thailand, Vietnam, Brazil, and Mexico was 25.1 million GBP, with projections rising to 398 million GBP by 2023. In South Korea, the market which includes food, feed, and medicinal products was valued at 109 million GBP in 2017 and was expected to quadruple by 2020. These trends underscore major opportunities for new businesses, particularly in developing regions, highlighting the economic potential of insects as a sustainable and high-value protein source [55].

Hurdles to wider adoption

Despite these opportunities, several significant challenges still limit the use of insects as food and feed. These challenges exist mainly because the field is still new and needs more scientific research and technological innovation. Key concerns include:

Anti-nutrient Properties

Insects contain chitin, a nitrogen-rich carbohydrate that makes up part of their exoskeleton. Some research suggests that chitin may reduce protein digestibility. For instance, when chitin was removed from dried honey bees, their protein digestibility and overall nutritional value improved. Despite this, chitin also offers important benefits. It is high in fiber and is already approved for use in foods in countries such as Japan. While humans generally cannot digest chitin directly, recent studies indicate that gut bacteria may produce enzymes capable of breaking it down. Chitosan, a derivative of chitin, has demonstrated health benefits in humans. In a two-week trial, consuming 3-6 grams per day led to a reduction in total cholesterol and an increase in HDL ("good") cholesterol. In poultry, chitin may support immune health and even reduce the need for antibiotics. Although these findings are promising, the long-term effects of chitin consumption in humans remain unclear, highlighting the need for further research [56].

Natural Compounds and Toxicity

Some insects naturally produce toxins, but most commonly consumed species are considered safe and do not belong to toxic categories. Research indicates that potentially harmful compounds such as hydrocyanide, oxalates, phytates, phenols, and tannins are generally present at levels well below those considered dangerous for human consumption. For example, analyses of Cirina forda larvae showed that oxalate and phytic acid levels were within safe limits, and no tannins were detected. Despite these reassuring findings, overall research on the nutritional composition and potential pharmacological effects of edible insects remains limited, highlighting the need for further studies [57].

Conclusion

Entomophagy the practice of eating insects presents a promising and sustainable approach to tackling global food security challenges. Edible insects are rich in high-quality protein, essential fatty acids, vitamins, and minerals, making them an attractive alternative to conventional animal-based foods. Beyond their nutritional benefits, insect farming is far more environmentally sustainable than traditional livestock production, requiring less land and water and generating fewer greenhouse gas emissions. This makes insects an appealing option for building a greener, more sustainable food system. Despite these advantages, several challenges remain. Consumer acceptance is limited in many regions, particularly in Western countries where insects are often associated with disgust or mistrust. Regulatory frameworks for farming, processing, and ensuring the safety of edible insects are still evolving, and potential allergenicity and toxicological risks must be fully understood. Continued research into safe processing methods, health effects, and standardized regulations will be essential to building confidence in insect-based foods. Public education and supportive policies can help overcome cultural and psychological barriers, encouraging wider acceptance. With growing interest in alternative protein sources and advancements in food technology, insect-based foods have the potential to transform the global food landscape. By safely integrating insects into our diets, we can move toward a more resilient, sustainable, and environmentally responsible food system capable of supporting future generations.

Reference

1. Gorbunova NA, Zakharov AN. Edible insects as a source of alternative protein. A review. Theory Pract Meat Process. 2021;6(1):23-32. DOI: 10.21323/2414-438X-2021-6-1-23-32.
2. Van Huis A. Edible insects contributing to food security? Agric Food Secur. 2015;4(1):20. DOI: 10.1186/s40066-015-0041-5.
3. Kraham SJ. Environmental impacts of industrial livestock production. In: Steier G, Patel KK, editors. International Farm Animal, Wildlife and Food Safety Law. Cham: Springer International Publishing; 2017. p. 3-40. DOI: 10.1007/978-3-319-18002-1_1.
4. Liceaga AM. Processing insects for use in the food and feed industry. Curr Opin Insect Sci. 2021;48:32-36. DOI: 10.1016/j.cois.2021.08.002.
5. Imathiu S. Benefits and food safety concerns associated with consumption of edible insects. NFS J. 2020;18:1-11. DOI: 10.1016/j.nfs.2019.11.002.
6. Oonincx DGA, Finke MD. Nutritional value of insects and ways to manipulate their composition. J Insects Food Feed. 2021;7(5):639-660. DOI: 10.3920/JIFF2020.0050.
7. Wade M, Hoelle J. A review of edible insect industrialization: scales of production and implications for sustainability. Environ Res Lett. 2020;15(12):123013. DOI: 10.1088/1748-9326/aba1c1.
8. European Food Safety Authority (EFSA). Risk profile related to production and consumption of insects as food and feed. EFSA J. 2015;13(10):4257. DOI: 10.2903/j.efsa.2015.4257.
9. Zielińska E, Baraniak B, Karaś M, Rybczyńska K, Jakubczyk A. Selected species of edible insects as a source of nutrient composition. Food Res Int. 2015;77:460-466. DOI: 10.1016/j.foodres.2015.09.008.
10. Raheem D, Carrascosa C, Oluwole OB, Nieuwland M, Saraiva A, Millán R. Traditional consumption of and rearing edible insects in Africa, Asia and Europe. Crit Rev Food Sci Nutr. 2019;59(14):2169-2188. DOI: 10.1080/10408398.2018.1440191.
11. Cortes Ortiz JA, Ruiz AT, Ramos MJA, Thomas M, Rojas MG, *et al*. Insect mass production technologies. In: Dossey AT, Morales-Ramos JA, Rojas MG, editors. Insects as Sustainable Food Ingredients. San Diego: Elsevier; 2016. p. 153-201. DOI: 10.1016/B978-0-12-802856-8.00006-5.
12. Finke MD, Oonincx D. Insects as food for insectivores. In: Morales-Ramos JA, Rojas MG, Shapiro-Ilan DI, editors. Mass Production of Beneficial Organisms. 2nd Ed. San Diego: Elsevier; 2023. p. 511-540. DOI: 10.1016/B978-0-12-822106-8.00019-1.
13. Caliceti C, Calabria D, Roda A, Cicero AFG. Agri-food waste from apple, pear, and sugar beet as a source of protective bioactive molecules for endothelial dysfunction and its major complications. Antioxidants. 2022;11(9):1786. DOI: 10.3390/antiox11091786.
14. Caliceti C, Calabria D, Roda A, Cicero AFG. Agri-food waste from apple, pear, and sugar beet as a source of protective bioactive molecules for endothelial dysfunction and its major complications. Antioxidants. 2022;11(9):1786. DOI: 10.3390/antiox11091786.
15. Rumpold BA, Schlüter OK. Nutritional composition and safety aspects of edible insects. Mol Nutr Food Res. 2013;57(5):802-823. DOI: 10.1002/mnfr.201200735.
16. Mujtaba M, Morsi RE, Kerch G, Elsabee MZ, Kaya M, Labidi J, *et al*. Chitosan-based delivery systems for plants: A brief overview of recent advances and future directions. Int J Biol Macromol. 2020;154:683-697. DOI: 10.1016/j.ijbiomac.2020.03.128.
17. Verbeke W, Spranghers T, Clercq DP, Smet DS, Sas B, Eeckhout M. Insects in animal feed: Acceptance and its determinants among farmers, agriculture sector stakeholders and citizens. Anim Feed Sci. Technol. 2015;204:72-87. DOI: 10.1016/j.anifeedsci.2015.04.001.
18. Garofalo C, Milanović V, Cardinali F, Aquilanti L, Clementi F, Osimani A. Current knowledge on the microbiota of edible insects intended for human consumption: A state-of-the-art review. Food Res Int. 2019;125:108527. DOI: 10.1016/j.foodres.2019.108527.
19. Gallo M, Ferrara L, Calogero A, Montesano D, Naviglio D. Relationships between food and diseases: what to know to ensure food safety. Food Res Int. 2020;137:109414. DOI: 10.1016/j.foodres.2020.109414.
20. Imathiu S. Benefits and food safety concerns associated with consumption of edible insects. NFS J. 2020;18:1-11. DOI: 10.1016/j.nfs.2019.11.002.
21. Ververis E, Ackerl R, Azzollini D, *et al*. A systematic review of the nutrient composition, microbiological and toxicological profile of *Acheta domesticus* (house cricket). J Food Compos Anal. 2022;114:104859. DOI: 10.1016/j.jfca.2022.104859.
22. Magara HJO, Niassy S, Ayieko MA, Mukundamago M, Egonyu JP, Tanga CM, *et al*. Edible crickets (Orthoptera) around the world: Distribution, nutritional value, and other benefits-a review. Front Nutr. 2021;7:537915. DOI: 10.3389/fnut.2020.537915.
23. European Food Safety Authority (EFSA). Risk profile related to production and consumption of insects as food and feed. EFSA J. 2015;13(10):4257. DOI: 10.2903/j.efsa.2015.4257.
24. Mole S, Zera AJ. Differential resource consumption obviates a potential flight-fecundity trade-off in the sand cricket (*Gryllus firmus*). Funct Ecol. 1994;8(5):573. DOI: 10.2307/2389917.
25. Kunatsa Y, Chidewe C, Zvidzai CJ, Phiri EE, Moyo S. Phytochemical and anti-nutrient composite from selected marginalized Zimbabwean edible insects and vegetables. J Agric Food Res. 2020;2:100027. DOI: 10.1016/j.jafr.2020.100027.

26. Sassi AB, Skhiri HF, Bourgou S, Wannes AW, Sellami HI, Tounsi SM, *et al*. Phytochemical profile and antiproliferative, anti-tyrosinase, antioxidant, and antibacterial potential of *Schinus terebinthifolius* growing in Tunisia. J Herbs Spices Med Plants. 2020;26(1):61-76. DOI: 10.1080/10496475.2019.1677277.
27. Yeerong K, Chaiyana W, Muangnoi C, Chansakaow S, Anuchapreeda S, Leelapornpisid P. *Acheta domesticus*: a natural source of anti-skin-aging ingredients for cosmetic applications. Pharmaceuticals (Basel). 2024;17(3):346. DOI: 10.3390/ph17030346.
28. Liu C, Wang C, Yao H, Chapman SJ. Comprehensive resource utilization of waste using the black soldier fly (*Hermetia illucens* (L.), (Diptera: Stratiomyidae). Animals (Basel). 2019;9(6):349. DOI: 10.3390/ani9060349.
29. Bargagli R, Rota E. Microplastic interactions and possible combined biological effects in Antarctic marine ecosystems. Animals (Basel). 2023;13(1):162. DOI: 10.3390/ani13010162.
30. Ravi HK, Venkatesh K, Prakash V, Shankar MA. Larvae mediated valorization of industrial, agriculture and food wastes: biorefinery concept through bioconversion, processes, procedures, and products. Processes. 2020;8(7):857. DOI: 10.3390/pr8070857.
31. Fuso A, Barbi S, Macavei LI, Luparelli AV, Maistrello L, Montorsi M, *et al*. Effect of the rearing substrate on total protein and amino acid composition in black soldier fly. Foods. 2021;10(8):1773. DOI: 10.3390/foods10081773.
32. Danieli PP, Lussiana C, Gasco L, Amici A, Ronchi B. The effects of diet formulation on the yield, proximate composition, and fatty acid profile of the black soldier fly (*Hermetia illucens* L.) prepupae intended for animal feed. Animals (Basel). 2019;9(4):178. DOI: 10.3390/ani9040178.
33. Kröncke N, Benning R. Self-selection of feeding substrates by *Tenebrio molitor* larvae of different ages to determine optimal macronutrient intake and the influence on larval growth and protein content. Insects. 2022;13(7):657. DOI: 10.3390/insects13070657.
34. Bonelli M, Bruno D, Caccia S, Sgambetterra G, Cappellozza S, Jucker C, *et al*. Black soldier fly larvae adapt to different food substrates through morphological and functional responses of the midgut. Int J Mol Sci. 2020;21(14):4955. DOI: 10.3390/ijms21144955.
35. Azelee NIW, Kadir R, Nordin N, Othman R, Zakaria Z, Zakaria ZA, *et al*. Sustainable valorization approaches on crustacean wastes for the extraction of chitin, bioactive compounds and their applications-a review. Int J Biol Macromol. 2023;253:126492. DOI: 10.1016/j.ijbiomac.2023.126492.
36. Gkinali AA, Grigorakis K, Kalogeropoulos N. Potentiality of *Tenebrio molitor* larva-based ingredients for the food industry: a review. Trends Food Sci Technol. 2022;119:495-507. DOI: 10.1016/j.tifs.2021.11.024.
37. Moruzzo R, Mancini S, Guidi A. Mealworm (*Tenebrio molitor*): potential and challenges to promote circular economy. Animals (Basel). 2021;11(9):2568. DOI: 10.3390/ani11092568.
38. Watt JC. A revised subfamily classification of Tenebrionidae (Coleoptera). N Z J Zool. 1974;1(4):381-452. DOI: 10.1080/03014223.1974.9517846.
39. Jankauskienė A, Žiugžda D, Bartkevičiūtė Z, Juodeikienė G. The influence of different sustainable substrates on the nutritional value of *Tenebrio molitor* larvae. Foods. 2024;13(3):365. DOI: 10.3390/foods13030365.
40. Dryden GMcL, editor. Animal Nutrition Science. 1st ed. Wallingford: CABI; 2008. DOI: 10.1079/9781845934125.0000.
41. Bordiean A, Krzyżaniak M, Teodorescu RI, Borda D, Apostol L, Ropciuc S. Influence of different diets on growth and nutritional composition of yellow mealworm. Foods. 2022;11(19):3075. DOI: 10.3390/foods11193075.
42. Silva JCM, Melo DJ, Pereira E, Oliveira DM, Pimentel TC, Esmerino EA, *et al*. Changes in the chemical, technological, and microbiological properties of kefir-fermented soymilk after supplementation with inulin and *Acrocomia aculeata* pulp. Appl Sci. 2021;11(12):5575. DOI: 10.3390/app11125575.
43. Anusha S, Negi PS. *Tenebrio molitor* (mealworm) protein as a sustainable dietary strategy to improve health span in D-galactose-induced aged mice. Int J Biol Macromol. 2024;281:136610. DOI: 10.1016/j.ijbiomac.2024.136610.
44. Adams GG, Imran S, Wang S, Mohammad A, Kok MS, Gray DA, *et al*. The hypoglycaemic effect of pumpkins as anti-diabetic and functional medicines. Food Res Int. 2011;44(4):862-867. DOI: 10.1016/j.foodres.2011.03.016.
45. Nemati F, Rahmani M, Sadeghi M, Shahraki MR, Alavi SM, Ghaderi E. Anti-inflammatory effects of anti-hypertensive agents: Influence on interleukin-1β secretion by peripheral blood polymorphonuclear leukocytes from patients with essential hypertension. Clin Exp Hypertens. 2011;33(2):66-76. DOI: 10.3109/10641963.2010.496521.
46. Jiang G, Wu Y, Li L, Li C, Chen Y, Zeng X. Strategies for sustainable substitution of livestock meat. Foods. 2020;9(9):1227. DOI: 10.3390/foods9091227.
47. Law W, Lansford T, Watson R. Obama's leadership in addressing climate change. In: Lansford T, Watson R, Covarrubias J, editors. Leadership and Legacy. Albany: SUNY Press; 2021, p. 267-287. DOI: 10.1515/9781438481883-014.
48. Booker K, Huntsinger L, Bartolome JW, Sayre NF, Stewart W. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? Glob Environ Change. 2013;23(1):240-251. DOI: 10.1016/j.gloenvcha.2012.10.001.
49. Aryal B, Neupane S, Panday D, Shrestha RK. Nitrous oxide emission in altered nitrogen cycle and implications for climate change. Environ Pollut. 2022;314:120272. DOI: 10.1016/j.envpol.2022.120272.
50. Valdés F, Cilia G, Galarza-Seeber R, Fusi E, Giromini C. Insects as feed for companion and exotic pets: A current trend. Animals (Basel). 2022;12(11):1450. DOI: 10.3390/ani12111450.
51. Azelee NIW, Kadir R, Nordin N, Othman R, Zakaria Z, Zakaria ZA, *et al*. Sustainable valorization approaches on crustacean wastes for the extraction of chitin,

bioactive compounds and their applications-a review. Int J Biol Macromol. 2023;253:126492. DOI: 10.1016/j.ijbiomac.2023.126492.
52. Tschirner M, Kloas W. Increasing the sustainability of aquaculture systems: Insects as alternative protein source for fish diets. GAIA. 2017;26(4):332-340. DOI: 10.14512/gaia.26.4.10.
53. Clark M, Tilman D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett. 2017;12(6):064016. DOI: 10.1088/1748-9326/aa6cd5.
54. Abbasi T, Abbasi T, Abbasi SA. Reducing the global environmental impact of livestock production: the minilivestock option. J Clean Prod. 2016;112:1754-1766. DOI: 10.1016/j.jclepro.2015.02.094.
55. Ainsworth P, Ibanoglu S, Plunkett A, Ibanoglu E, Stojceska V. Effect of brewers spent grain addition and screw speed on the selected physical and nutritional properties of an extruded snack. J Food Eng. 2007;81(4):702-709. DOI: 10.1016/j.jfoodeng.2007.01.004.
56. Thomas JA. Monitoring change in the abundance and distribution of insects using butterflies and other indicator groups. Philos Trans R Soc. Lond. B Biol. Sci. 2005;360(1454):339-357. DOI: 10.1098/rstb.2004.1585.
57. Al Seadi T, Rutz D, Prassl H, Köttner M, Finsterwalder T, Volk S, *et al*. Biomass resources for biogas production. In: Wellinger A, Murphy J, Baxter D, editors. The Biogas Handbook. Cambridge: Elsevier; 2013, p. 19-51. DOI: 10.1533/9780857097415.1.19.