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Harnessing insects for novel feed products in agricultural waste management: Review

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Abstract: The growing demand for sustainable protein in animal production has increased interest in insects as alternative feed ingredients, especially in poultry nutrition. Insects are nutrient-rich, providing high-quality protein, lipids, essential amino acids, and bioactive compounds that support growth, health, and feed efficiency. Black soldier fly larvae (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Acheta domesticus*) are among the most studied species, showing potential to replace conventional protein sources such as soybean meal and fishmeal. Insect-based feeds improve nutrient utilization, gut health, and reduce environmental impact by valorizing agricultural and food by-products, contributing to circular economy models. This review evaluates the nutritional, environmental, and regulatory aspects of insect-based feeds. A comprehensive synthesis of recent literature was conducted, focusing on composition, functional properties, safety, and sustainability. Findings indicate that *Hermetia illucens*, *Tenebrio molitor*, and *Acheta domesticus* provide high-quality protein and bioactive compounds that enhance poultry growth performance and feed efficiency. Insect utilization transforms organic waste into protein-rich biomass, reducing environmental impact. However, large-scale adoption is limited by production costs, regulatory inconsistencies, and safety concerns. Practical implications stress the need for standardized safety and quality frameworks, cost-effective mass-rearing technologies, and long-term feeding trials. Overall, insect farming offers a sustainable strategy to enhance resource efficiency, food security, and environmental resilience in animal production.

Keywords: *Acheta domesticus, Agricultural waste management, Sustainable protein sources, Hermetia illucens, Tenebrio molitor, Insect-based feed.*

1. Introduction

Global meat production has experienced significant growth, with notable regional variations driven by economic development, population growth, and shifting dietary preferences.

In 2024, global meat production is estimated to have risen by 1.3%, reaching 365 Mt. This growth was led largely by poultry meat, with beef output increases also contributing, while pig and sheep meat production remained stable. Significant growth in meat production occurred in Australia, Brazil, the European Union, and the United States. Among these, Brazil registered the most significant expansion across all major meat categories, driven by strong global demand, supported by higher net returns due to a favorable exchange rate and lower feed costs, as well as continued disease-free status [1].

The global meat industry faces ongoing challenges, including rising feed costs, sustainability concerns, and environmental degradation [2]. Traditional protein sources like soybean meal and fishmeal contribute to overfishing and market volatility [3].

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By 2034, global livestock stocks (cattle, sheep, pigs, and poultry, measured in cattle equivalent units) are expected to increase by 7%, while meat, dairy, and egg production (measured on a protein basis) is projected to increase by 16.6%, reflecting increased livestock productivity. This trend is particularly notable in lower-middle-income countries, where livestock numbers are expected to increase by 10% and production by 43.6%. These productivity gains are driven by intensified feeding practices, which, combined with larger animal populations, are expected to boost global feed consumption by 15% (on a protein-equivalent basis).

Global variations in production efficiency stem from differences in technologies, livestock management, feeding practices, and access to high-quality feed. The OECD-FAO Agricultural Outlook 2025–2034 projects long-term trends in agricultural and fish commodity markets, driven by rising incomes and urbanization, which are increasing global demand for animal-derived foods. This demand drives expanded production of animal-source foods, spurring growth in the feed market to support intensified livestock and aquaculture systems [1].

However, population growth, urbanization, and economic development are also escalating waste generation, with global waste production projected to reach approximately 2.6 billion tonnes by 2030 and 3.4 billion tonnes by 2050, nearly doubling 2016 levels and tripling by 2100 [4].

Agricultural waste, such as crop residues, food processing by-products, and organic matter, presents significant environmental and economic challenges. Converting this waste into high-quality feed using insects offers a sustainable alternative to conventional ingredients, reducing dependence on environmentally harmful resources and promoting a circular economy in agriculture [5] and enhancing feed sustainability, and supporting eco-friendly agricultural practices.

2. Materials and Methods

A systematic literature review was conducted to evaluate the potential of insects for novel feed products and agricultural waste management by synthesizing findings from peer-reviewed studies published between 2010 and 2025. The review utilized academic databases, including Scopus, Web of Science, PubMed, and Google Scholar.

Studies were selected based on inclusion criteria requiring a focus on insect species such as black soldier fly (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*), or crickets (*Acheta domesticus*) for bioconversion of agricultural waste into feed, evaluation of nutritional composition, feed efficiency, or environmental benefits, and discussion of scaling or regulatory challenges.

Data were extracted on insect species, waste substrates (e.g., crop residues, fruit peels, brewery waste, manure), bioconversion efficiency metrics (waste reduction index, feed conversion ratio, nutrient recovery), nutritional profiles (protein, fat, chitin content), and environmental impacts (greenhouse gas emissions, land use).

Key studies, such as Surendra et al. [6], emphasized the bioconversion efficiency of *Hermetia illucens* and *Tenebrio molitor*, highlighting their commercial potential with substrates like food waste and manure, and detailed substrate pre-treatment methods, such as grinding and moisture adjustment, to optimize larval consumption, using control substrates like standard feed for comparison.

Nutritional profiles were analyzed by Henry et al. [5] using methods such as protein content analysis, Soxhlet extraction, or gas chromatography for fat, and enzymatic assays or spectrometry for chitin and micronutrients, with comparisons to conventional feeds like soybean meal and fishmeal [2].

The environmental impacts were assessed using Life Cycle Assessments (LCAs), with insects demonstrating lower impacts compared to conventional feed sources [7].

Ethical and regulatory considerations were reviewed based on FAO and EU guidelines, addressing feed safety, public perception, and legal barriers [8].

This review offers a comprehensive framework for understanding the role of insects in transforming agricultural waste into sustainable feed products, encompassing scientific, practical, and regulatory perspectives.

3. Results and Discussion

3.1. Feed Innovations for Sustainable Agriculture

Global consumption of agricultural and fish commodities is projected to rise by 13% from current levels by 2034, with nearly all additional demand expected to originate from middle- and low-income countries. This increase will be driven primarily by expanding, more affluent, and increasingly urbanized populations in these regions. By 2034, annual per capita consumption is anticipated to grow by 0.9 kg per person (edible retail weight equivalent, rwe). In high-income countries, growing concerns about animal welfare, environmental impacts, and health are leading to stagnating or declining per capita meat consumption in some cases.

The rise in global consumption is primarily driven by expected increases in poultry and bovine meat production, alongside a modest rise in ovine meat. In contrast, pig meat production is projected to decrease slightly. Since 1961, Asia and South America have seen the most significant increases in meat production, fueled by demographic growth and economic development. Meanwhile, Europe's slower production growth reflects a shift toward efficiency-driven systems, which could serve as a model for global sustainability (Table 1).

Table 1.
Total meat production**,** (tonnes).

Country or region	1961	2023	Absolute Change	Relative Change
Africa	3,909,681 t	22,775,330 t	+18,865,650 t	+483%
Asia	9,034,635 t	163,494,220 t	+154,459,585 t	+1,710%
Europe	29,454,630 t	55,653,324 t	+26,198,694 t	+89%
North America	19,582,326 t	64,294,730 t	+44,712,404 t	+228%
Oceania	2,296,940 t	7,182,189 t	+4,885,249 t	+213%
South America	6,516,068 t	49,464,904 t	+42,948,837 t	+659%

Source: aFAO [9].

This rapid expansion in meat production significantly increases the demand for animal feed, putting pressure on agricultural systems. To address environmental and resource constraints, innovative and sustainable feed production methods are essential. These include adopting alternative protein sources, such as insect-based feeds, and improving feed conversion efficiencies to meet livestock nutritional needs while minimizing ecological impacts.

Animal feed is projected to remain a critical component of the integrated food chain in the future. The Food and Agriculture Organization (FAO) emphasizes the urgent need to identify sustainable alternatives to conventional feed ingredients, given their limited availability (Food and Agriculture Organization of the United Nations) [10].

Traditionally, the diets of monogastric animals such as poultry and swine rely heavily on protein sources, including fishmeal, processed animal proteins, dairy by-products, soybean meal (SBM), rapeseed meal, and canola meal. However, the cost of these conventional protein sources has risen substantially, driven by restricted production capacity and increasing competition between human consumption and animal nutrition [11]. In this context, the growing global population and the rising costs of traditional feed ingredients underscore the necessity of developing alternative protein sources to ensure long-term sustainability in animal production.

At the same time, the issue of food and agricultural waste offers a complementary perspective. As the global population expands and the demand for food increases, the importance of implementing efficient waste management strategies becomes more evident. Research conducted in Europe shows that agricultural waste accounts for approximately 15% of total food loss and waste, amounting to nearly 88 million tons annually [12]. This underscores the significant potential of revalorizing agricultural by-products and waste streams as valuable resources, rather than treating them solely as disposal challenges.

Insects efficiently bioconvert organic waste into new products, mirroring the principle of a circular economy, providing benefits such as reduced waste management costs and resource use in protein and fat production through insect-derived feed [13].

Currently, more than 2,100 species of edible insects are consumed by approximately two billion people across more than 113 countries [14].

As the market for edible insects continues to expand, they are increasingly recognized as a valuable food and feed source.

3.2. Insect-Based Feed Products

Intensified agricultural production systems use significant external inputs to increase yields, but they also destabilize ecosystems [15]. Biodiversity is key to sustainable agricultural production and, more broadly, a livable planet. Understanding the role of insects in ecosystems will aid in achieving this goal.

The practice of consuming insects, known as entomophagy, has gained recognition as a promising strategy to address future global food challenges, including malnutrition, food insecurity, and the rising demand for animal-derived proteins [16-19].

Projections indicate that by 2050, global food demand is expected to increase by approximately 50%, while the need for animal protein could rise by as much as 70% [16]. In response, the global edible insect sector has attracted growing attention from both industry and academia, as evidenced by the emergence of numerous start-ups and a substantial increase in scientific publications over the past decade. Current market analyses suggest that the edible insect industry could reach an estimated value of USD 8 billion within the next ten years [20].

Insects represent a sustainable option for converting waste into highly nutritious food for both animals and humans. Interest in insects as a protein source is increasing due to the rising costs of conventional proteins such as meat, fish meal, and soybean meal [21-23].

Globally, approximately 1,500 edible insect species are consumed across 113 countries and 300 ethnic groups. Traditionally, insects have served as a valuable nutrient source, providing 5–10% of dietary animal protein along with fats, calories, vitamins, and minerals in certain communities [24, 25].

Edible insects have also garnered interest in food and feed applications due to their notable nutritional and functional properties. Research consistently demonstrates that insects represent a high-quality nutrient source, providing substantial amounts of protein, essential amino acids, dietary fiber, mono- and polyunsaturated fatty acids, vitamins, and minerals, often at levels comparable to those of conventional livestock proteins [17, 26].

Beyond their nutritional value, edible insects are associated with potential health-promoting effects, including antioxidant, antihypertensive, anti-inflammatory, antimicrobial, and immunomodulatory activities. These benefits are attributed to the presence of bioactive compounds such as phenolics, chitin, chitosan, fatty acids, and bioactive peptides, which collectively contribute to enhanced nutritional and physiological outcomes for consumers.

From a sustainability perspective, edible insects present a notable advantage over conventional livestock species. One of the most relevant parameters in this regard is the proportion of edible biomass. Insects provide an edible fraction ranging from 80% to nearly 100% of their body mass, whereas in traditional livestock species such as poultry, pork, and beef, only 40–55% is typically consumed. This substantial difference highlights the superior efficiency of insects as a protein source and underscores their potential role in reducing food loss and waste, thereby contributing to the development of more sustainable food production systems (Figure 1).

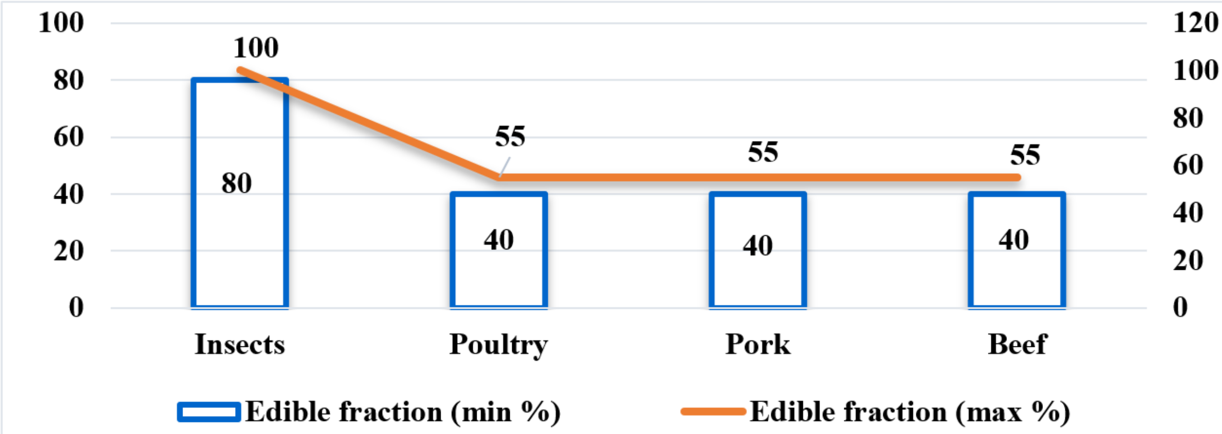

Figure 1.
Comparative edible fraction of insects vs conventional livestock.

The information presented outlines insect species suitable for human consumption, with only seven currently used as feed, primarily in their larval stage (Table 2).

Table 2.
Major insect species are farmed for food and/or feed.

Scientific Name	Common Name	Developmental Stage	Food	Feed
Acheta domesticus	House cricket	Adult	x	x
Tenebrio molitor	Mealworm	Larvae	x	x
Gryllus bimaculatus	Mediterranean field cricket	Adult		x
Bombyx mori	Silkworm	Larvae, pupae	x	x
Galleria mellonella	Wax worm	Larvae	x	
Apis mellifera	European honeybee	Adult	x	
Musca domestica	Common housefly	Larvae		x
Lucilia sericata	Common green bottle fly	Larvae (maggot)		x
Rhynchophorus ferrugineus	Red palm weevil	Larvae, pupae	x	
Rhynchophorus phoenicis	Palm weevil	Larvae	x	
Pachnoda marginata	Sun beetle	Larvae	x	x
Hermetia illucens	Black soldier fly (BSF)	Larvae	x	x

Source: Cortes Ortiz et al. [27] and Varelas [28].

The preference for larvae in both food and feed applications can be attributed to their high protein content, well-balanced amino acid composition, and relatively efficient rearing requirements. In contrast, species such as the European honeybee and the wax moth are generally not employed as feed, likely due to their unique biological traits or greater economic and ecological value in other roles.

These observations highlight the significant potential of insects as a sustainable and resource-efficient alternative for food and feed, with mealworm larvae, black soldier fly larvae, and house crickets standing out as the most promising candidates in this context.

3.3. Black Soldier Fly (Hermetia Illucens)

The Black Soldier Fly (*Hermetia illucens*) stands out as a cornerstone species, widely recognized for its exceptional ability to convert organic waste into nutrient-rich biomass, thereby addressing two critical challenges simultaneously: sustainable waste management and the production of alternative protein sources. Similarly, mealworm larvae and house crickets demonstrate substantial potential in waste bioconversion pathways, reinforcing their contribution to the advancement of environmentally sound feed solutions within a circular bioeconomy framework.

The larvae of the Black Soldier Fly (*Hermetia illucens*) are capable of efficiently processing a wide range of organic substrates, including food waste, agricultural by-products, and manure, into protein- and lipid-rich biomass. This remarkable bioconversion capacity is largely attributed to their potent digestive enzymes, such as proteases, lipases, and amylases, which enable the rapid degradation of organic material [29, 30]. The larvae are particularly effective in processing substrates such as fruit and vegetable residues, bakery by-products, cereal bran, husks, and livestock manure. Through this process, they can reduce waste volume by 50–70% while simultaneously producing frass, a nutrient-rich by-product that serves as a valuable organic soil amendment [3, 31]. Consequently, *H. illucens* has emerged as an effective biological tool for waste management and the reduction of environmental impact. Nutritionally, *H. illucens* larvae represent a valuable source of proteins and lipids (Table 3).

Table 3.
Nutritional composition of *Hermetia illucens* larvae (dry matter basis).

Parameter	Average value	References
Dry matter (%)	90–92	Barragan-Fonseca et al. [29]
Protein (% of DM)	40–45	Makkar et al. [2] and Van Huis and Oonincx [11]
Lipids (% of DM)	25–35	Spranghers et al. [32]
Ash (% of DM)	10–15	Meneguz et al. [33]
Lysine (% of protein)	5.5–6.0	Makkar et al. [2]
Methionine (% of protein)	2.0–2.5	Van Huis and Oonincx [11]
Calcium (% of DM)	5.0–8.0	Biasato et al. [34]
Phosphorus (% of DM)	0.6–1.0	Meneguz et al. [33]
Major fatty acid	Lauric acid (C12:0), 30–50% of total fat	Spranghers et al. [32]

On a dry matter basis, they typically contain 40–45% protein with a favorable amino acid profile, including essential amino acids such as lysine and methionine, comparable to soybean meal and fishmeal [2, 11]. Their lipid content ranges between 25–35%, dominated by medium-chain fatty acids, particularly lauric acid, which exhibits antimicrobial properties and provides a readily available energy source [32, 35, 36]. These nutritional attributes make *Hermetia illucens* highly suitable as a feed ingredient for poultry, fish, swine, and companion animals. Moreover, the extracted lipid fraction can be utilized as a feed additive or biofuel source, further enhancing its versatility. The nutritional composition of *Hermetia illucens* larvae shows notable variation depending on substrate and rearing conditions (Figure 2).

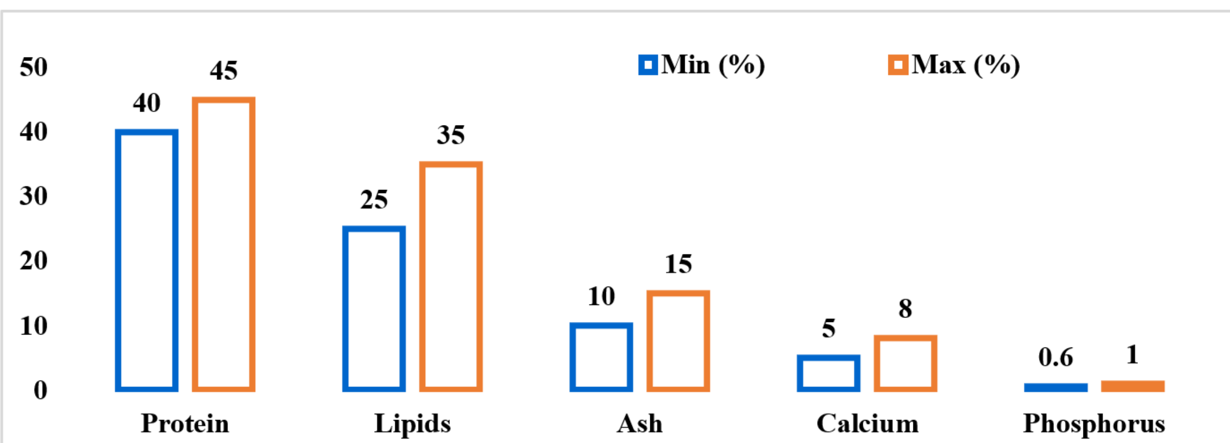

Figure 2.
Nutritional composition of Black Soldier Fly larvae (% of dry matter)

Protein levels range between 40–45% of dry matter, remaining relatively stable across studies. In contrast, lipid content demonstrates wider fluctuations (25–35%), largely influenced by the type of organic substrate provided. Ash content varies between 10–15%, while mineral fractions such as calcium (5–8%) and phosphorus (0.6–1.0%) also exhibit moderate variability. Overall, the data highlight that while protein levels are consistently high, lipids and minerals show greater sensitivity to environmental and dietary factors.

Experimental studies confirm that replacing 10–50% of conventional protein sources in poultry diets with *H. illucens* larvae supports growth performance and feed efficiency without negative impacts on animal health [34, 37]. Beyond feed, the bioconversion process yields frass, a nutrient-rich organic residue that can be applied as fertilizer, thereby contributing to soil fertility and sustainable crop production [33, 38].

Black soldier fly larvae (BSFL) rapidly process diverse organic wastes, reducing substrate mass by up to 50% more efficiently than conventional composting. Larval growth is strongly influenced by substrate composition, with high-lignin and cellulose materials, such as dairy manure, showing limited digestibility. Pretreatment methods can improve both biodegradability and nutrient availability [39].

Hermetia illucens presents an efficient and sustainable approach for converting low-value organic waste into high-quality feed ingredients, simultaneously promoting nutrient recycling and waste reduction. Despite challenges related to regulatory compliance, economic feasibility, and scalability, its environmental, nutritional, and economic benefits highlight its potential as a key resource for sustainable feed production and circular economy frameworks [40, 41].

Substrate enrichment with nutrient-dense materials, such as soybean curd residue or chicken manure, combined with microbial fermentation of lignocellulosic waste, further enhances nutrient release and larval performance [42]. Optimal development of BSFL requires a careful balance between substrate moisture and nutrient content. Consequently, BSFL are increasingly adopted as a sustainable protein source in animal feed, with cultivation practices aligned to regional regulatory standards.

3.4. Mealworms (Tenebrio molitor)

Mealworms (*Tenebrio molitor*) larvae are valued as an insect-based protein source due to their high nutritional content (protein and fat) [43-45], good digestibility [46], favorable flavor [44], and functional compounds such as chitin and antimicrobial peptides (AMPs) [47, 48].

They are easy to rear, maintain stable protein levels regardless of diet, and can thus be produced reliably. For these reasons, *T. molitor* larvae are industrially cultivated as feed for pets, zoo animals, and production animals, including fish, pigs, and poultry [46].

The proximal composition of *Tenebrio molitor* varies significantly across its life stages and by-products (Table 4).

Table 4.
Proximal content of *Tenebrio molitor* larvae, adult, exuvium, and excreta (percent, dry basis).

Component	Larvae	Adult	Exuvium	Excreta
Moisture	5.33	3.54	13.02	12.2
Crude protein	46.44	63.34	32.87	18.51
Crude fat	32.7	7.59	3.59	1.3
Crude fiber	4.58	19.96	25.96	13.66
Crude ash	2.86	3.56	3.22	7.29

Source: Ravzanaadii, et al. [49].

Larvae are rich in protein (46.44%) and fat (32.7%), making them highly valuable as an energy-dense feed. Adults have the highest protein content (63.34%) but much lower fat (7.59%), while exuvium and excreta are poorer in protein and fat but contain higher fiber (25.96% in exuvium) and ash (7.29% in excreta). Overall, larvae are ideal for protein and energy supplementation; adults serve as a concentrated protein source; and exuvium and excreta may provide fiber and mineral contributions in animal diets. Additionally, mealworms provide all essential amino acids in adequate amounts [50, 51].

The comparative analysis (Table 5) revealed that *Tenebrio molitor* contains significantly higher levels of most essential amino acids, particularly lysine, phenylalanine, histidine, and valine, compared to *Hermetia illucens.* At the same time, *H. illucens* provides tryptophan, which is absent in *T. molitor*, adding specific value in animal nutrition. Therefore, mealworms can be considered a more complete protein source, while black soldier fly larvae remain promising due to their waste bioconversion capacity and are best suited for inclusion in combined diets.

Table 5.
Amino acid profiles (mg/g) of insects.

Essential amino acid	Hermetia illucens	Tenebrio molitor
Histidine	0.44–0.49	2.97–17.16
Isoleucine	0.51–0.56	3.17–9.18
Leucine	0.84–0.87	5.58–9.95
Lysine	0.44–0.69	5.11–15.26
Methionine	0.28–0.29	0.71–2.98[1]
Phenylalanine	0.57–0.74	7.93–13.41[2]
Tryptophan	0.12–0.13	-
Threonine	0.39–0.43	2.55–5.96
Valine	0.58–0.63	3.67–11.34
[1]Total methionine and cysteine content [2]Total phenylalanine and tyrosine content	[52, 53]	[54-56]

Mealworms are recognized as a valuable source of zinc and are particularly rich in magnesium, although their calcium content is relatively low [57]. The analysis of the mineral content in *Tenebrio molitor* (Table 6) reveals that calcium increases from larvae (434.59 mg/kg) to excreta (1,537.97 mg/kg), while phosphorus and potassium reach their highest levels in excreta (14,552.01 mg/kg and 21,171.75 mg/kg, respectively), indicating intensive mineral excretion.

Exuviae are particularly rich in calcium (801.14 mg/kg) and zinc (265.18 mg/kg), reflecting their structural role in the cuticle. Iron and copper concentrations are slightly higher in adults (78.71 and 18.01 mg/kg, respectively), suggesting their involvement in metabolic processes, whereas magnesium peaks in excreta (7135.14 mg/kg). Overall, the distribution demonstrates that larvae and adults represent valuable mineral sources, while exuviae and excreta concentrate essential macro- and microelements, underscoring their potential for nutrient recycling and agricultural applications.

Table 6.
Mineral content of *Tenebrio molitor* larvae, Adult, Exuvium, and Excreta (mg of mineral/kg of sample).

Mineral		Larvae	Adult	Exuvium	Excreta
Calcium (Ca)		434.59	484.39	801.14	1537.97
Phosphorus (P)		7060.7	8087.07	5252.29	14552.01
Potassium (K)		9479.73	10459.8	14725.66	21171.75
Iron (Fe)		66.87	78.71	55.86	127.75
Natrium (Na)		3644.84	4302.73	6343.16	3954.33
Magnesium (Mg)		2026.88	1932	1388.09	7135.14
Zinc (Zn)		104.28	108.98	265.18	101.31
Copper (Cu)		13.27	18.01	10.04	10.73

Source: Ravzanaadii et al. [49].

They are also considered a source of niacin and contain high levels of pyridoxine, riboflavin, folate, and vitamin B_{12} [57]. Comparative analyses with conventional meats indicate that mealworms offer a substantially higher overall nutritional value than beef and chicken, while maintaining a similarly balanced nutrient profile [58].

Mealworms (*Tenebrio molitor L*) can be effectively reared on a variety of agricultural residues and other low-quality organic substrates, demonstrating adaptability to diverse feeding materials [59]. Due to their favorable growth performance and nutritional composition, they represent a promising alternative protein source for livestock, particularly monogastric animals [60].

Thus, *T. molitor* larvae possess high-quality and abundant protein, along with a well-balanced amino acid profile, making them a highly sustainable alternative protein source to soybean meal (SBM) or fishmeal. *T. molitor* larvae have already been used as feed ingredients in animal diets. Several studies have been conducted to evaluate the use of *T. molitor* larvae in monogastric animal diets.

In studies by Zacharis et al. [61], *Tenebrio molitor* larvae were used as a feed ingredient for young pigs. The larvae were reared either on a standard substrate or on a substrate enriched with aromatic plant compounds. Thirty-six weaned piglets (34 days old) were divided into three groups of 12 and fed for 42 days with a standard diet (Group A), a diet containing 10% larval meal from larvae reared on the standard substrate (Group B), or a diet containing 10% larval meal from larvae reared on the enriched substrate (Group C).

All groups showed comparable growth rates and feed intake. Blood analysis indicated that the inclusion of larval meal affected total cholesterol levels but did not impact other biochemical parameters. Meat samples exhibited differences in microbial populations, higher total phenolic content, and varied fatty acid profiles, while their appearance and color remained similar across groups.

Šťastník et al. [62] investigated the effects of dietary inclusion of yellow mealworm (Tenebrio molitor L.) meal in broiler chickens. Two experimental groups received diets containing 2% and 5% mealworm meal, while a control group received none. Inclusion of mealworm meal did not alter the chemical composition or sensory quality of thigh meat. However, control birds showed higher final body weight and feed intake ($P < 0.05$), and their breast meat was rated superior in taste compared to the experimental groups.

In other studies, conducted by Nuraini et al. [63] and Nuraini et al. [64], the potential of Tenebrio molitor larvae as a dietary ingredient for laying quails was investigated. The experiments were designed as a completely randomized design (CRD) with five dietary treatments and four replicates per treatment. The inclusion levels of *T. molitor* larvae were 0%, 3%, 6%, 9%, and 12% of the total diet, replacing fish meal.

The results demonstrated that dietary inclusion of *T. molitor* larvae did not significantly affect ($P > 0.05$) feed intake, egg production, egg weight, egg mass, or feed conversion ratio. These findings suggest that *T. molitor* larvae can be incorporated into the diets of laying quails at levels up to 12% as a complete replacement for fish meal, without compromising productive performance. This highlights the potential of *T. molitor* larvae as a sustainable alternative protein source in quail nutrition [65].

The impact of incorporating Hong Kong caterpillars (*Tenebrio molitor larvae*) into the diet of quails on egg quality was also investigated. The study involved 200 quails, aged 8–14 weeks, with an average weight of 110 ± 10 g and a 40% egg-laying productivity. Diets for laying quails were formulated with varying levels of Hong Kong caterpillar meal (HKC): 0% HKC for Group A, 3% HKC for Group B, 6% HKC for Group C, 9% HKC for Group D, and 12% HKC for Group E. The results demonstrated that including 12% HKC in the quail diet significantly reduced cholesterol and fat content in egg yolks. However, eggshell thickness and protein content in egg whites remained unchanged across all groups [66, 67].

In poultry studies, the inclusion of *T. molitor* larvae improved growth performance in broiler chickens without negatively affecting carcass traits, although some studies reported no significant differences in growth performance or carcass yield. In swine studies, *T. molitor* larvae enhanced growth and protein utilization in weaned piglets. Furthermore, inclusion of 10% *T. molitor* larvae demonstrated better amino acid digestibility compared to conventional animal proteins in growing pigs. However, certain challenges remain regarding biosafety, consumer acceptance, and the cost of using *T. molitor* larvae in animal feeds. Therefore, *T. molitor* larvae can be considered as an alternative or sustainable protein source in monogastric animal diets, taking into account their nutritional value.

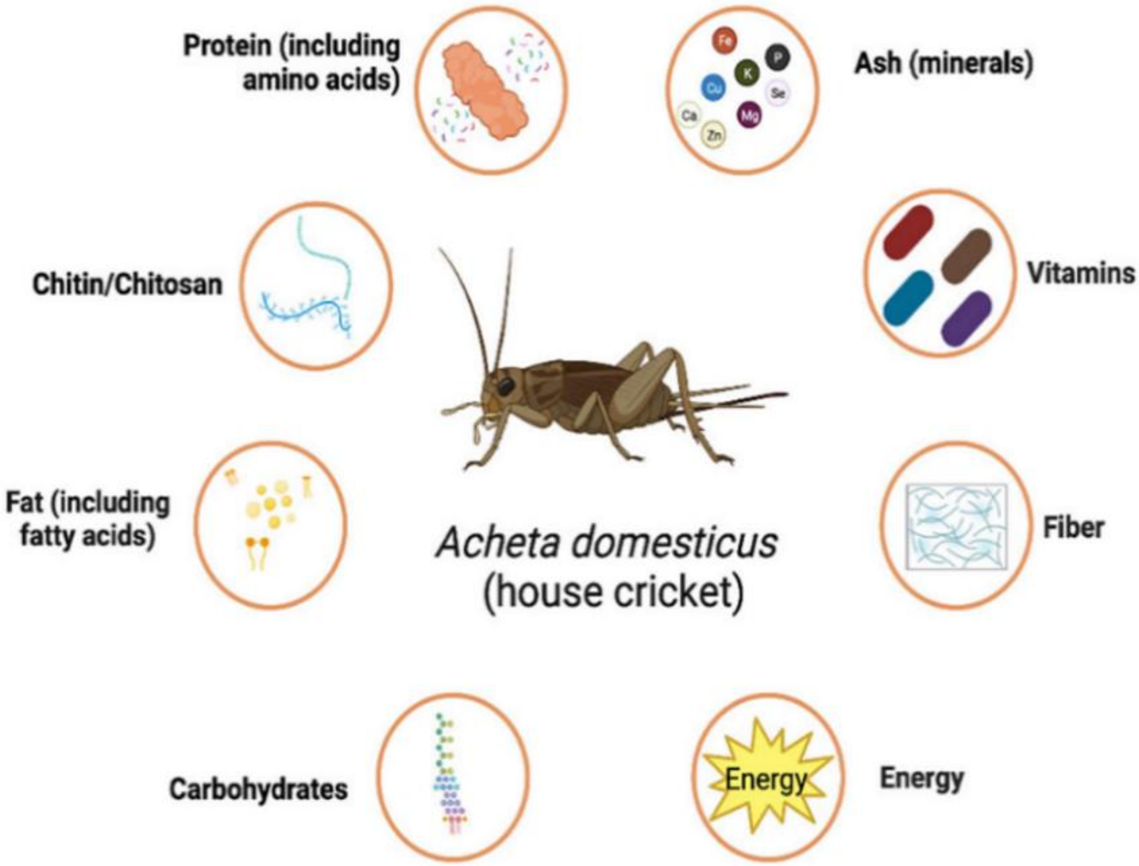

Figure 3.
Nutritional composition of Acheta domesticus (house cricket), including proteins (with amino acids), fats (with fatty acids), carbohydrates, chitin/chitosan, vitamins, minerals (ash), fiber, and the energy they provide.

3.5. Crickets (Acheta Domesticus)

Among edible insects, the house cricket (*Acheta domesticus*) is attracting growing interest as a novel protein and nutrient source, offering the food industry a safe and eco-friendly alternative with significant biological value. The house cricket (*Acheta domesticus*) is considered one of the most promising reared insects due to its attractive nutritional profile and lower feed conversion ratio compared to other animals. *Acheta domesticus* (house cricket) was recently approved by Commission Implementing Regulation (EU) 2022/188 as a novel food ingredient. House cricket holds promise as a sustainable alternative to traditional farming and conventional food sources due to its nutritional and pharmaceutical properties.

The suitability of house crickets for integrated indoor cultivation is being explored to assess various cultivation conditions, such as innovative composite materials that are appropriate for co-cultivating them with other organisms, such as macroalgae (Figure 3) [65].

In studies, conducted by Udomsil et al. [66], a comparative evaluation revealed clear nutritional distinctions between the two cricket species A. domesticus and G. bimaculatus. A. domesticus displayed significantly higher levels of moisture (6.3% vs. 3.0%; $p < 0.001$), protein (71.7% vs. 60.7%; $p < 0.001$),

ash (5.4% vs. 2.8%; $p < 0.001$), and carbohydrates (1.6% vs. 0.1%; $p < 0.001$), underscoring its profile as a protein- and mineral-rich species.
By contrast, G. bimaculatus exhibited a nutritional pattern dominated by markedly higher lipid (23.4% vs. 10.4%; $p < 0.001$) and fiber content (10.0% vs. 4.6%; $p < 0.001$), which differentiates it as a more energy-dense and fiber-enriched species (Table 7, Figure 4).

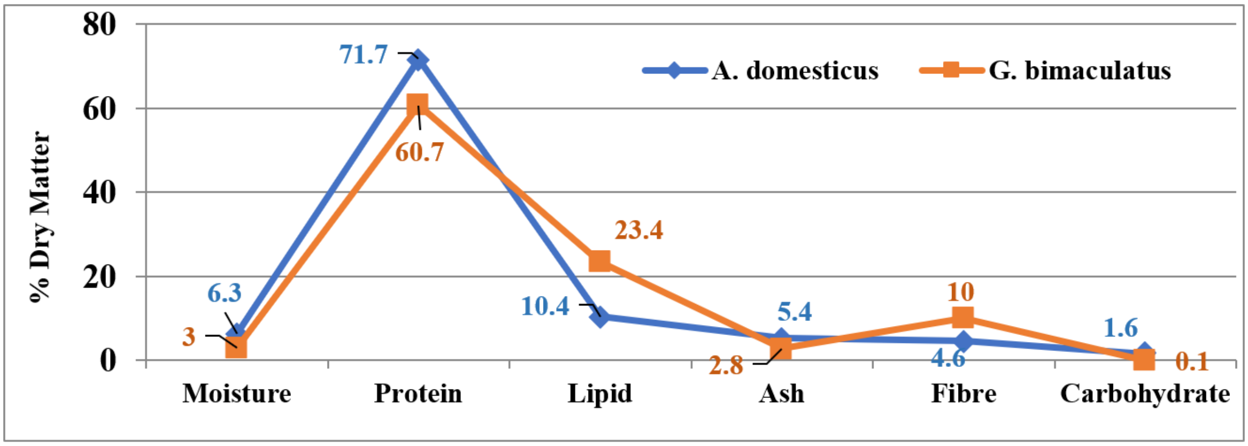

Figure 4.
Proximate Nutrient Composition (% Dry Matter).

Table 7.
Proximate and Mineral Composition of *Acheta domesticus* (Dry Matter Basis).

% Dry matter	**A. domesticus**
Moisture	5.40 ± 0.04
Proteins	48.36 ± 0.2*
Lipid	12.70 ± 0.01
Fiber	7.70 ± 0.3*
Carbohydrates	17.30 ± 0.1*
Ash	8.50*
Mineral contents, mg/100 g dry matter	
Calcium (Ca)	145. 75 ± 4. 13*
Sodium (Na)	100. 44 ± 4. 80*
Potassium (K)	380. 92 ± 0. 38*
Phosphorus (P)	800. 33 ± 3. 19*
Magnesium (Mg)	400. 58 ± 4. 90
Iron (Fe)	6. 83 ± 1. 80
Copper (Cu)	4. 86 ± 1. 35
Manganese (Mn)	3. 40 ± 1. 08
Zinc (Zn)	20. 61 ± 0. 83*

Note: Values are expressed as means ± standard deviations of triplicate analyses.
Data means were compared with A. domesticus using Student's t-test * $p < 0.05$.

These interspecific differences are also reflected in their mineral composition: *A. domesticus* contained substantially higher concentrations of calcium, potassium, phosphorus, magnesium, copper, manganese, and zinc ($p < 0.05$–0.001), whereas both species presented comparable levels of sodium and iron (Figure 5) [66].

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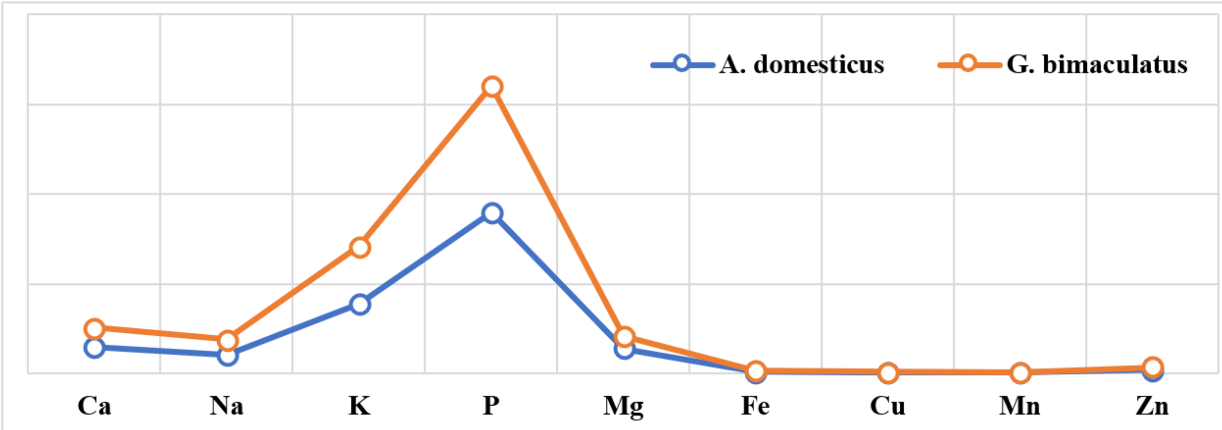

Figure 5.
Mineral Content (mg/100 g Dry Matter).

Overall, the findings highlight that although taxonomically related, the two species offer distinct nutritional advantages: *A. domesticus* is particularly suitable for applications that require high-quality protein and mineral supplementation, whereas *G. bimaculatus* is more advantageous for energy-dense and fiber-rich dietary formulations. These differences underscore the potential for the selective utilization of each species in the food and feed industry, allowing producers to tailor insect-based products according to specific nutritional requirements, whether for human consumption or animal diets.

Nieto et al. [68] investigated the impact of substituting soybean meal with cricket meal (Acheta domesticus) on the growth performance of slow-growing chickens. The trial involved 16 experimental groups, each comprising 8 birds, which were assigned to two dietary treatments formulated to be isoproteic and isoenergetic but differing in protein source. The control group (C) was fed a soybean meal-based diet, while the Acheta group (AD) received Acheta domesticus meal as the primary protein ingredient.

The findings indicated that diets containing A. domesticus meal reduced feed intake during the first month, which in turn negatively affected body weight. Thus, during the first four weeks of life, only partial replacement of soybean meal is advisable, as higher inclusion levels of cricket meal at this stage appear to be unfavorable for chick development.

Nevertheless, given the lack of significant differences in overall performance parameters between treatments, the study suggests that A. domesticus meal could represent a promising alternative protein source to soybean meal in poultry nutrition.

In other studies, conducted by Nakagaki et al. [69], two controlled feeding trials were performed to evaluate the protein quality of dried cricket (*Acheta domesticus*) meal in broiler chicken diets. In the first trial, semi-purified diets were designed to identify limiting amino acids. Although no statistically significant differences in body weight gain were observed among birds receiving amino acid–acid-supplemented diets, the feed conversion ratio indicated that arginine, methionine, and tryptophan were likely the most limiting amino acids in cricket-based diets.

In the second trial, dried cricket meal was incorporated into practical diets by replacing soybean meal as the primary protein source. Comparable weight gains were observed between chickens fed corn–soybean diets and those receiving corn–cricket diets. Nevertheless, feed conversion efficiency improved significantly with the supplementation of methionine and arginine, suggesting that while cricket meal constitutes a promising alternative to soybean meal, careful balancing of essential amino acids is required to optimize growth performance.

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Recent reports indicate that dogs are able to consume insect-based diets without negative consequences for health or nutrient digestibility, supporting the potential of insects as sustainable protein sources in companion animal nutrition. Among the most promising candidates are the pupae of the house cricket (*Acheta domesticus*, AD) and the silkworm (*Bombyx mori*, BM), which provide high-quality protein and could serve as suitable alternatives to conventional poultry and fish meals.

Feeding trials with healthy adult mixed-breed dogs have further supported this perspective. In one study, animals were divided into groups and fed diets with varying inclusion levels of AD or BM (7–20% of daily intake) for 29 days. The evaluation of blood parameters and nutrient digestibility revealed no adverse effects, and diets containing up to 20% AD or 14% BM successfully replaced poultry meal without compromising health or nutrient utilization.

These findings highlight the feasibility of incorporating insect meals into canine diets and suggest that, with appropriate formulation, insects may represent a sustainable and nutritionally adequate alternative protein source for pet food production.

In studies conducted by Fitroh et al. [70], the effect of dietary cricket flour inclusion on quail production performance was evaluated. A total of 240 female quails (47 days old) were assigned to four treatments: 100% basal feed (P0), and basal feed supplemented with 5% (P1), 10% (P2), or 15% (P3) cricket flour. The results showed that feed intake, egg production, and egg mass increased significantly with higher levels of cricket flour, while feed conversion ratio improved accordingly. The best performance was observed in P3 (15% cricket flour), suggesting that this inclusion level is optimal for enhancing quail productivity.

Overall, these findings are consistent with other studies demonstrating that insect-based ingredients can enhance nutrient utilization, growth, and reproductive performance in both poultry and livestock [2, 71-73].

Beyond their nutritional benefits, crickets and other edible insects represent an ecologically sustainable alternative to conventional protein sources, as their production requires considerably less land, water, and energy while generating lower greenhouse gas emissions [3, 31, 41]. Thus, the inclusion of cricket flour in animal diets not only improves production efficiency but also supports the transition toward more sustainable feed resources. These results add to the growing body of evidence suggesting that insect-based feed ingredients hold significant promise for the future of poultry and livestock nutrition in the context of global food security and environmental sustainability [5, 13].

3.6. Advances in Insect-Based Feed Production and Environmental Benefits

Insect-based feed production has emerged as a promising solution to address the growing global demand for sustainable and nutritious animal feed. This approach offers several environmental benefits, including reduced greenhouse gas emissions, lower land and water usage, and the ability to recycle organic waste into valuable protein sources for livestock and aquaculture.

Studies have demonstrated that insect-based feeds can enhance growth performance, feed conversion ratios, and overall health in various livestock species, including poultry, swine, and fish [74]. Insects such as black soldier flies (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Acheta domesticus*) are rich in proteins, essential amino acids, lipids, vitamins, and minerals. Their nutritional profile makes them suitable substitutes for conventional feed ingredients like fishmeal and soybean meal. High feed conversion efficiency further enhances their environmental value; for example, crickets require only 2.1 kg of feed per 1 kg of body mass, compared to over 12 kg for cattle. Additionally, rearing insects on food scraps and agricultural by-products reduces waste and lowers the overall ecological footprint [75, 76].

The scalability of insect farming presents both opportunities and challenges. While initial investments can be high, long-term benefits include reduced feed costs, waste valorization, and alignment with rising consumer demand for sustainable and ethical products. Regulatory frameworks, however, remain a key constraint. In the EU, for instance, the use of insect-derived proteins in poultry and pig feed is authorized but subject to species-specific safety assessments. Consumer acceptance is also a limiting factor in some markets due to cultural perceptions and limited awareness of benefits.

Businesses globally face complex regulatory and market pressures that influence strategy, operations, and competitiveness. Regulatory requirements, including environmental standards, legislative changes, and data protection laws such as GDPR and CCPA, necessitate continuous adaptation [77]. Simultaneously, market dynamics, including competition, technological disruption, and shifting consumer preferences, demand investment in innovation, product differentiation, and advanced analytics.

Effective firms integrate regulatory compliance into strategic planning, leverage technology, and develop partnerships with regulators and tech providers to foster innovation and resilience. Technological transformation, including AI, IoT, and blockchain, alongside consumer trends for sustainability, requires ongoing adaptation to maintain a competitive advantage.

Future research should focus on optimizing insect rearing, improving processing technologies, and standardizing regulations. Selective breeding for rapid growth and disease resistance could further enhance efficiency and sustainability.

Insect-based feeds offer a viable, environmentally friendly alternative to conventional feed sources. By harnessing their nutritional value, ecological benefits, and waste-recycling potential, insects can contribute significantly to a sustainable and resilient agricultural system. Addressing regulatory hurdles and fostering consumer acceptance will be essential for broad adoption.

4. Conclusion

Insects present a transformative opportunity for agricultural waste management by converting by-products into sustainable, nutrient-rich feed. They are a sustainable and nutritionally rich alternative protein source for poultry feeding, supplying high-quality protein, essential amino acids, lipids, and bioactive compounds that support growth, health, and feed efficiency. By valorizing organic by-products and reducing reliance on conventional protein sources, insects also enhance environmental sustainability.

While challenges related to production, safety, regulation, and consumer acceptance remain, ongoing advancements in mass-rearing technologies, standardized safety measures, policy frameworks, and market strategies are paving the way for broader adoption. Integrating insect-based feeds into livestock and poultry production offers opportunities to improve resource efficiency, promote circular economy models, and strengthen food security, highlighting their potential as a promising solution for sustainable livestock nutrition.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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