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Insect-based feed ingredients in poultry nutrition: Entomological innovations and nutritional implications for sustainable livestock production

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Abstract
The escalating demand for sustainable animal protein sources has intensified the search for alternative feed ingredients in poultry production. Insects, long overlooked in mainstream agriculture, are now gaining global recognition as viable components of poultry diets due to their high protein content, efficient feed conversion, and low environmental footprint. This review explores the intersection between poultry nutrition and entomology, focusing on the application of insect-derived meals—particularly black soldier fly larvae (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and housefly larvae (*Musca domestica*)—as novel protein sources in poultry feeding programs.

We examine the nutritional profiles of commonly farmed insect species, including crude protein levels, amino acid composition, lipid content, and bioactive compounds, and how these attributes vary with rearing conditions, substrate, and developmental stage. From an entomological perspective, the paper reviews mass-rearing technologies, life cycle optimization, and biosecurity protocols relevant to feed safety and scalability. Performance metrics such as growth rate, feed conversion ratio, egg production, and meat quality in poultry are analyzed alongside health-related benefits such as improved gut microbiota and immune modulation.

The review also addresses potential constraints, including chitin content, anti-nutritional factors, and risks of microbial contamination, as well as regulatory and consumer acceptance challenges. Finally, we identify key research gaps and propose integrative strategies to enhance the economic viability, safety, and acceptance of insect-based feeds within circular agricultural systems. By bridging entomological insights with poultry nutritional science, this paper contributes to the discourse on sustainable livestock feeding strategies in the face of global food security challenges.

Keywords: Insect meal, poultry nutrition, sustainable livestock feed, hermetia illucens, circular agriculture

Introduction
The global livestock industry is under increasing pressure to meet the rising demand for animal protein while simultaneously minimizing its environmental footprint and dependency on conventional feed resources. Poultry production, in particular, is the fastest-growing segment of the livestock sector due to its relatively low resource input and rapid turnover rate (FAO, 2020) [10]. However, the sector's reliance on conventional protein sources such as soybean meal and fishmeal raises concerns related to deforestation, overfishing, price volatility, and geopolitical instability (Makkar *et al*., 2014) [17]. These challenges have driven a growing interest in alternative, sustainable feed ingredients that can ensure food security, enhance resource efficiency, and support environmental stewardship.

Among the emerging solutions, insects have garnered attention as promising feed ingredients due to their exceptional feed conversion efficiency, high protein and lipid content, and ability to grow on organic waste substrates (van Huis *et al*., 2013) [26]. Entomological innovations in insect farming have further facilitated the scalability and commercial viability of insect-based feeds, positioning them as a viable option for poultry nutrition. Species such as the black soldier fly (*Hermetia illucens*), mealworm (*Tenebrio molitor*), and housefly larvae (*Musca domestica*) are increasingly being evaluated for their nutritional potential and compatibility with poultry digestive physiology (Sogari *et al*., 2019) [22].

This review explores the multidisciplinary intersection of entomology and poultry nutrition by critically examining the use of insect-derived meals in poultry feed formulations. It addresses the nutritional composition of edible insects, entomological advances in insect farming, impacts on poultry growth performance and health, safety considerations, and regulatory challenges. In doing so, the paper aims to provide a comprehensive understanding of how insect-based feed ingredients can contribute to the sustainability and resilience of the poultry industry in the face of global resource constraints and climate change.

Edible Insects in Focus
The selection of insect species for use in poultry diets is a critical consideration shaped by factors such as nutritional composition, rearing efficiency, lifecycle characteristics, and local adaptability. Among the most commonly researched and farmed insect species for feed are the black soldier fly (*Hermetia illucens*), mealworm (*Tenebrio molitor*), and housefly larvae (*Musca domestica*). Each species offers unique advantages that make them suitable for incorporation into poultry feed, both nutritionally and logistically (Makkar *et al*., 2014) [17].

The black soldier fly (BSF) has gained significant attention in the past decade due to its rapid growth, high protein yield, and ability to thrive on a wide variety of organic waste materials. BSF larvae can be harvested within 14 to 18 days under optimal conditions and typically yield a dry matter protein content of 35% to 45%, with lipid content ranging from 15% to 35% (Henry *et al*., 2015) [13]. Additionally, BSF larvae are rich in antimicrobial peptides and lauric acid, compounds known to support poultry immune function and gut health (Spranghers *et al*., 2017) [23].

Mealworms, the larval form of the darkling beetle (*Tenebrio molitor*), are another protein-rich insect used in poultry nutrition. With a protein content of approximately 50% on a dry matter basis, they also contain beneficial fatty acids, vitamins, and minerals (Rumpold & Schlüter, 2013) [21]. Mealworms are particularly efficient in controlled rearing environments and have shown promise in enhancing meat quality and growth rates when included at moderate levels in poultry diets.

Housefly larvae (*Musca domestica*) represent one of the oldest forms of insect-based feed, particularly in traditional and smallholder poultry systems. These larvae are efficient converters of organic waste and contain around 40% to 55% crude protein, along with essential amino acids such as lysine and methionine (Elahi *et al*., 2022) [9]. Despite their potential, concerns about microbial contamination and consumer perception persist, emphasizing the need for standardized processing protocols.

Overall, the entomological diversity among edible insect species offers a broad foundation for developing tailored insect-based feed solutions. The selection of species must consider not only nutritional adequacy and rearing feasibility but also the socio-economic and environmental contexts of poultry production systems.

Nutritional Profile of Insect Meals

The nutritional composition of insect-based meals is one of their most compelling attributes for poultry feed formulation. Insects generally provide a rich source of protein, lipids, essential amino acids, and micronutrients, although these values can vary significantly depending on species, developmental stage, and rearing substrate (Rumpold & Schlüter, 2013) [21].

Protein content across commonly used insect species typically ranges from 35% to 65% on a dry matter basis. For example, *Tenebrio molitor* (mealworm) larvae contain approximately 50% crude protein, while *Hermetia illucens* (black soldier fly) larvae range between 35% and 45%. *Musca domestica* (housefly) larvae can also yield up to 55% protein when reared under optimal conditions (Henry *et al*., 2015; Elahi *et al*., 2022) [9, 13]. These protein levels are comparable to or even higher than conventional sources such as soybean meal (44–48%) and fishmeal (60–72%).

In addition to protein quantity, the amino acid profile of insect meals is particularly noteworthy. Most edible insects are rich in lysine, threonine, and methionine—amino acids critical for poultry growth and immune function, yet often limited in plant-based feeds (Makkar *et al*., 2014) [17]. Furthermore, black soldier fly larvae are known to be high in lauric acid, a medium-chain fatty acid with antimicrobial properties that supports gut health and pathogen resistance in poultry (Spranghers *et al*., 2017) [23].

Insects also provide beneficial lipids, with total fat content ranging from 15% to 35% depending on the species and stage of development. For instance, BSF larvae can have up to 30% lipid content, including saturated and unsaturated fatty acids essential for energy metabolism. While high fat levels may necessitate defatting for certain poultry feed applications, the inclusion of moderate levels of insect-derived fats has been shown to enhance feed palatability and energy density (van Huis *et al*., 2013) [26].

Micronutrient contributions from insect meals include vitamins such as riboflavin, biotin, and vitamin B12, as well as trace minerals like calcium, iron, zinc, and phosphorus (Rumpold & Schlüter, 2013) [21]. These nutrients support metabolic functions, bone development, and immune competence in poultry.

Despite the promising nutritional profile, variability in nutrient composition due to differences in rearing substrates, environmental conditions, and processing methods remains a challenge. Standardization and quality control measures are necessary to ensure consistent feed value and to facilitate commercial adoption. Nonetheless, the nutrient-dense nature of insect meals offers significant potential to enhance the nutritional balance and functional benefits of poultry diets.

Entomological Advances in Insect Farming

The rise of insects as a sustainable feed source has been made possible by significant advances in insect farming technologies, largely driven by entomological research. Controlled rearing systems have evolved from small-scale, manual operations to automated, climate-controlled facilities capable of producing large volumes of insect biomass with consistent quality. These innovations have improved production efficiency, enhanced biosecurity, and reduced the environmental footprint of insect farming (van Huis & Oonincx, 2017) [25].

One of the key developments is the optimization of rearing conditions—such as temperature, humidity, and photoperiod—to accelerate insect growth and increase protein yield. For example, *Hermetia illucens* larvae show optimal development at temperatures between 27–30°C with relative humidity around 60–70% (Holmes *et al*., 2012) [14]. Additionally, research into substrate formulation has shown that the nutritional composition of the feed substrate greatly influences the proximate composition of the resulting larvae. Agro-industrial by-products such as fruit waste, brewer's grains, and food scraps have been successfully used to rear BSF and housefly larvae at scale (Barragan-Fonseca *et al*., 2017) [1].

Reproductive efficiency has also been a focus of entomological innovation. For instance, artificial lighting regimes and the use of attractants have been developed to enhance adult mating and oviposition in BSF, addressing one of the early bottlenecks in mass rearing (Tomberlin *et al*., 2009) [24].

Moreover, integrated bioconversion systems have emerged, wherein insect farming is embedded within circular economy models. These systems not only reduce organic waste but also produce frass (insect excreta) as a secondary product usable as a soil amendment (Parodi *et al*., 2022) [20]. Such developments support both economic and environmental sustainability in poultry feed supply chains.

Despite these advances, challenges remain, including the need for further automation, improved genetic selection for feed traits, and harmonization of global standards. Continued collaboration between entomologists, animal nutritionists, and engineers will be essential to realize the full potential of insect farming for poultry nutrition.

Poultry Performance and Health Outcomes

Numerous studies have investigated the effects of insect-based feed ingredients on poultry performance metrics, including body weight gain, feed intake, feed conversion ratio (FCR), immune responses, and product quality. Results across these studies generally support the nutritional efficacy of insects when incorporated at appropriate levels in poultry diets.

In broilers, the inclusion of black soldier fly (*Hermetia illucens*) larvae meal at levels between 5% and 20% has been shown to maintain or even improve growth performance compared to conventional protein sources (Mwaniki *et al*., 2020) [19]. Birds fed 10% BSF meal exhibited similar body weight gain and FCR to those on a soybean meal-based diet, while higher inclusion levels may require amino acid supplementation to balance the profile (Cullere *et al*., 2016) [6].

Mealworms (*Tenebrio molitor*) have also demonstrated favorable effects in broiler diets. Diets containing up to 10% mealworm meal have resulted in improved nutrient digestibility and carcass yield, particularly in the finisher phase (Bovera *et al*., 2016) [4]. Similarly, housefly larvae meal has been reported to support satisfactory growth and nutrient retention in broilers at inclusion rates of up to 15% (Elahi *et al*., 2022) [9].

For laying hens, moderate inclusion levels of insect meals (typically 5–10%) have been associated with sustained or slightly enhanced egg production, better yolk pigmentation due to natural carotenoids, and stable shell quality (Mishyna *et al*., 2021) [18]. Moreover, insects like BSF provide bioactive components such as lauric acid and antimicrobial peptides, which have been linked to improved gut health and disease resistance (Spranghers *et al*., 2017) [23].

In terms of immune modulation, insect meals have been shown to enhance immunoglobulin levels, stimulate macrophage activity, and reduce intestinal pathogen loads (Borrelli *et al*., 2017) [3]. These functional benefits suggest that insects are more than just protein sources—they may serve as nutraceuticals that positively influence poultry health and productivity.

However, performance outcomes can vary depending on insect species, diet formulation, inclusion level, and bird genetics. High inclusion rates without balancing essential amino acids may impair performance. Additionally, defatting may be necessary to optimize protein density and reduce excess energy in finisher diets (Makkar *et al*., 2014) [17].

Overall, existing literature supports the integration of insect-based ingredients in poultry nutrition, not only as a sustainable protein alternative but also as a functional feed component capable of improving performance and health outcomes.

Processing and Feed Safety

While insects offer strong nutritional and functional benefits as poultry feed ingredients, their safety and processing methods are critical to ensuring product quality, regulatory compliance, and consumer trust. Improper handling during production, harvesting, and storage can lead to microbial contamination, accumulation of heavy metals, and the presence of anti-nutritional compounds—all of which can pose health risks to poultry and, indirectly, to human consumers (EFSA, 2015) [7].

One of the most significant concerns is microbial contamination, particularly from pathogenic bacteria such as *Salmonella spp.* and *Escherichia coli*, which may be present in the rearing substrate or introduced during processing. Thermal processing methods such as blanching, drying, or extrusion have been shown to significantly reduce microbial loads, improving the microbial safety of insect meals (Bessa *et al*., 2020) [2]. Insects like the black soldier fly are often reared on organic waste, which necessitates rigorous substrate screening and hygiene control to mitigate bioaccumulation risks.

Heavy metal accumulation, especially of cadmium, lead, and arsenic, is another concern, particularly for species reared on contaminated substrates. Studies have demonstrated that the concentration of heavy metals in insect meals can be influenced by the type and source of feed substrate, requiring careful selection and monitoring (Charlton *et al*., 2015) [5].

Chitin, a structural polysaccharide present in the exoskeleton of insects, may act as a dietary fiber with prebiotic benefits but can also hinder protein digestibility at high levels. Processing techniques such as defatting and enzymatic treatment are being explored to reduce chitin content and improve digestibility and nutrient availability (Rumpold & Schlüter, 2013) [21].

In addition, lipid-rich insect meals are prone to oxidative rancidity if not properly dried and stored. The use of vacuum packaging, antioxidant supplementation, and moisture control are essential strategies to maintain product stability during storage and transport (Bessa *et al*., 2020) [2].

Ultimately, the development of standardized processing protocols and safety assessments—including hazard analysis and critical control points (HACCP)—will be crucial to scale the commercial use of insect meals in poultry nutrition. Regulatory frameworks, such as those established by the European Food Safety Authority (EFSA) and other national agencies, provide guidance on processing, labeling, and permissible substrates, contributing to the safe integration of insects into animal feed systems (EFSA, 2015) [7].

Regulatory Frameworks and Consumer Acceptance

The integration of insect-based meals into poultry nutrition is not solely a matter of nutritional science and entomological innovation—it also hinges on supportive regulatory environments and public acceptance. Globally, the regulatory landscape surrounding the use of insects in animal feed is evolving, with varying degrees of approval, oversight, and public engagement.

In the European Union, the European Food Safety Authority (EFSA) has authorized the use of certain insect species—including *Hermetia illucens*, *Tenebrio molitor*, and *Musca domestica*—for aquaculture feed since 2017 and expanded this to poultry and swine in 2021, under strict substrate and hygiene conditions (EFSA, 2021) [8]. Regulatory frameworks emphasize traceability, substrate quality, microbial risk management, and labeling transparency. These protocols are designed to ensure safety and build consumer confidence in the integrity of insect-derived products.

In the United States, the Food and Drug Administration (FDA) regulates insect feed ingredients under the Generally Recognized as Safe (GRAS) criteria, although formal approval processes vary by species and intended use. Similar regulatory efforts are underway in countries such as Canada, South Africa, Nigeria, and Kenya, reflecting growing global interest in mainstreaming insect protein (FAO, 2021) [11].

Consumer acceptance remains a critical bottleneck, especially in regions where entomophagy is not culturally prevalent. Studies indicate that public perception of insect-based animal feeds is shaped by factors such as perceived naturalness, hygiene, food safety, and ethical concerns

(Verbeke *et al*., 2015) [27]. Insect meals used for poultry are often more acceptable to consumers than direct human consumption of insects, particularly when the end-product (e.g., eggs or meat) shows no visible trace of the insect component (Mishyna *et al*., 2021) [18].

To enhance market penetration, education campaigns, transparent labeling, and public engagement are essential. Integrating sustainability messaging—highlighting reduced land use, greenhouse gas emissions, and waste recycling benefits—has been shown to positively influence consumer attitudes (Sogari *et al*., 2019) [22].

As regulatory clarity improves and public awareness grows, the commercial use of insect-based feeds in poultry systems is expected to expand. However, cross-sector collaboration between scientists, policymakers, producers, and communication experts will be vital to bridge the gap between technical feasibility and public trust.

Environmental and Socioeconomic Considerations

The environmental and socioeconomic dimensions of insect-based poultry feed are among the most compelling arguments for its broader adoption. Insects possess a remarkably efficient feed conversion ratio (FCR), require minimal land and water resources, and can be reared on organic waste streams—attributes that collectively align with the principles of circular agriculture and climate-smart food systems (van Huis & Oonincx, 2017) [25].

Compared to traditional livestock feed crops such as soybean and maize, insects such as *Hermetia illucens* generate significantly lower greenhouse gas emissions and ammonia production, while also producing high-quality protein in a fraction of the space and time (Parodi *et al*., 2022) [20]. These advantages make insect farming an attractive component of integrated waste management systems. Organic waste from agro-industries, households, and food processing can be diverted to insect bioconversion units, where it is transformed into protein-rich biomass and organic fertilizer (frass), effectively closing nutrient loops (Barragan-Fonseca *et al*., 2017) [1].

From a socioeconomic perspective, insect farming offers opportunities for decentralized, low-tech, and scalable enterprises that are accessible to smallholder farmers and rural communities. In low- and middle-income countries (LMICs), this can contribute to job creation, income diversification, and improved food security (FAO, 2021) [11]. Gender-inclusive value chains are also increasingly being promoted, particularly in Africa and Southeast Asia, where women play significant roles in insect rearing and processing (Halloran *et al*., 2016) [12].

However, to realize these benefits at scale, investments in training, infrastructure, quality control, and market access are essential. Policies supporting subsidies, research, and public-private partnerships can catalyze the development of a vibrant insect economy that not only supplements poultry feed demands but also uplifts marginalized groups and mitigates environmental degradation.

The confluence of ecological efficiency and rural development potential positions insect-based poultry feed as a transformative solution for sustainable agriculture, especially in the context of mounting resource constraints and the need for resilient food systems.

Research Gaps and Future Directions

Despite the growing body of evidence supporting insect-based feed in poultry production, several research gaps remain that must be addressed to facilitate its mainstream adoption. One of the foremost challenges is the lack of species-specific nutritional standards. While insects like *Hermetia illucens* and *Tenebrio molitor* have been extensively studied, the optimal inclusion levels, amino acid balancing, and defatting requirements for different poultry species and developmental stages are still not fully established (Makkar *et al*., 2014) [17].

Another critical area is the standardization of rearing and processing conditions. Nutritional composition can vary significantly depending on substrate, rearing environment, and post-harvest handling. This variability complicates the formulation of consistent, high-quality feeds and requires harmonized guidelines for industry-wide quality assurance (Rumpold & Schlüter, 2013) [21].

There is also a pressing need for long-term feeding trials that assess not only growth performance but also reproductive parameters, disease resistance, gut microbiota modulation, and overall welfare. Current studies are often limited to short-term or single-phase observations, leaving gaps in our understanding of chronic exposure and cumulative effects (Borrelli *et al*., 2017) [3].

Further research is needed into the bioavailability of micronutrients and the functional role of bioactive compounds such as antimicrobial peptides, chitin, and lauric acid. While these compounds offer potential health benefits, their mechanisms of action and effective dosages remain poorly understood (Spranghers *et al*., 2017) [23].

From an economic and policy standpoint, comprehensive cost-benefit analyses and lifecycle assessments are needed to compare insect-based feeds with conventional alternatives across diverse production systems. This includes understanding the scalability of insect farming technologies and their integration into existing value chains (Parodi *et al*., 2022) [20].

Finally, greater interdisciplinary collaboration among entomologists, animal nutritionists, food scientists, economists, and policy experts is essential to drive innovation and ensure the responsible development of insect-based feed industries. Bridging these gaps will be key to unlocking the full potential of insects in sustainable poultry nutrition.

The State of Insect-Based Poultry Feed in Nigeria

Nigeria is emerging as a significant player in the adoption of insect-based protein for poultry feed, driven by the need to reduce reliance on imported feed ingredients and to address the escalating costs of conventional protein sources (FAO, 2021) [11]. The country's favorable climate, abundant organic waste resources, and growing entrepreneurial interest make it well-suited for insect farming, particularly of the black soldier fly (*Hermetia illucens*).

Several initiatives have been launched to promote insect farming in Nigeria. The Insects4Feed Cluster, a collaboration between Nigerian and Dutch partners, aims to provide high-quality feed and fertilizer for livestock farmers using black soldier fly larvae. This initiative not only addresses food insecurity by improving access to protein but also offers income-generating opportunities for women and youths through training in insect rearing (Insects4Feed, 2023) [16].

Research indicates that insect-based animal feeds and their by-products could represent a $250 million to $1.2 billion opportunity for Nigeria by 2030 (How We Made It in

Africa, 2023) [15]. This potential is attributed to the ability of insects to convert organic waste into valuable protein sources for animal feed, thereby establishing a circular value chain that reduces food waste and provides sustainable feed alternatives (Parodi *et al*., 2022) [20].

Despite these promising developments, challenges remain. There is a need for increased awareness and acceptance of insect-based feeds among farmers, as well as the establishment of regulatory frameworks to ensure the safety and standardization of insect-derived feed products (EFSA, 2021) [8]. Moreover, scaling up production to meet the growing demand requires investment in infrastructure and capacity building.

In conclusion, Nigeria's efforts in developing insect-based poultry feed are gaining momentum, with significant economic and environmental benefits on the horizon. Continued support from government, research institutions, and private sector stakeholders will be crucial in overcoming existing challenges and realizing the full potential of this sustainable feed alternative.

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Conclusion

Insects present a compelling solution to the dual challenges of sustainable poultry production and global food security. Their high nutritional value, efficient feed conversion, and capacity for organic waste bioconversion position them as versatile, environmentally friendly alternatives to conventional protein sources. Through advances in entomological research, insect farming has evolved into a scalable and scientifically grounded enterprise capable of contributing meaningfully to poultry nutrition.

This review has examined the multifaceted potential of insect-based feed ingredients, encompassing their nutritional profiles, effects on poultry performance and health, processing and safety considerations, regulatory status, and environmental and socioeconomic benefits. While current findings are largely positive, realizing the full benefits of insect meals will depend on addressing critical research gaps, improving processing standards, and fostering public trust through transparent communication and regulatory oversight.

The successful integration of insects into poultry feeding systems requires a collaborative, interdisciplinary approach involving scientists, policymakers, farmers, and industry stakeholders. With continued investment in research, infrastructure, and education, insects can become a cornerstone of climate-resilient and resource-efficient poultry production systems.

As the world moves toward more sustainable agricultural practices, the entomological innovations explored in this review offer not only a technical advancement but also a paradigm shift in how we approach livestock nutrition and planetary health.

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