JOURNAL OF AGRICULTURE AND LIVESTOCK FARMING
Jan-Mar 2025, VOL. 2, ISSUE 1, pp. 10-13
https://doi.org/10.61577/jalf.2025.100003

RESEAPRO JOURNALS

MINI REVIEW

OPEN ACCESS

Insect-Based protein in livestock feed: A sustainable alternative to conventional feedstocks

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ABSTRACT

Insect-based proteins are gaining traction as a sustainable alternative to conventional livestock feed ingredients, such as soybean meal and fishmeal, which are associated with deforestation, overfishing, and greenhouse gas emissions. Insects such as black soldier fly larvae (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Acheta domesticus*) offer high protein content, efficient feed conversion, and can be reared on organic waste, contributing to a circular economy. These insect-based feeds possess favorable amino acid profiles and beneficial lipids, and show high digestibility and animal acceptance across species. Their role in improving animal health through gut microbiota modulation and antimicrobial properties adds further value. This mini-review highlights their nutritional value, performance outcomes in poultry, swine, and aquaculture, and examines their role in reducing the ecological footprint of animal agriculture. It also outlines the environmental benefits of insect farming, including waste valorization, emission reduction, and integration into mixed farming systems, while addressing current limitations such as regulatory gaps, safety concerns, and market barriers. Integrating insect meals into feed strategies not only supports productivity but also aligns with global sustainability targets and enhances climate resilience. With appropriate research, public awareness, and policy support, insect protein could become a mainstream component of sustainable animal agriculture.

KEYWORDS

Sustainable livestock feed; Black soldier fly; Circular economy; Feed innovation; Alternative protein

ARTICLE HISTORY

Received 4 February 2025; Revised 6 March 2025; Accepted 17 March 2025

Introduction

The projected global population increase to nearly 10 billion by 2050, alongside dietary shifts toward animal-sourced food, will significantly increase demand for livestock products. Consequently, this growth places tremendous stress on the agricultural sector, especially on feed production systems [1]. Conventional feed ingredients such as soybean meal and fishmeal are unsustainable due to their link with land degradation, water depletion, and high greenhouse gas emissions [2]. Soybean expansion in South America is linked to deforestation, while fishmeal production contributes to overfishing and the degradation of marine habitats. Additionally, these conventional ingredients are subject to price volatility and global trade disruptions, which compromise feed security in low- and middle-income countries [3].

The livestock industry accounts for approximately 14.5% of total anthropogenic greenhouse gas emissions, with feed production representing a significant portion of this footprint [4]. The environmental costs associated with growing feed crops, such as fertilizer use, irrigation, and land conversion, compound the urgency to find more sustainable alternatives. Moreover, the demand for protein-rich feed continues to grow as meat consumption increases globally, especially in developing economies where livestock serves as a major income and nutrition source [5].

As global awareness of these challenges intensifies, attention is turning to insect farming as a low-input, high-efficiency protein solution. Insects such as black soldier fly larvae (BSFL), mealworms, and crickets have garnered interest due to their excellent nutrient profiles, low environmental impact, and compatibility with waste-to-protein systems [6]. These species can convert low-value organic materials, including food scraps, brewery waste, and agricultural by-products, into high-protein biomass. Additionally, their short life cycles, rapid reproduction, and ability to grow on a variety of substrates make them especially attractive for scalable feed production [7].

Insect farming offers a decentralized approach to protein production, allowing both industrial and smallholder systems to participate. In countries with limited arable land or water resources, insect farming can complement or replace imported feed ingredients, strengthening local food sovereignty. Insect meal also supports circular agriculture by closing nutrient loops and producing valuable co-products such as biofertilizers from insect frass [8].

This review explores the potential of insect meal as an animal feed alternative, focusing on its nutritional value, digestibility, production scalability, livestock performance, and sustainability benefits. It also discusses the limitations, regulatory gaps, and necessary steps to mainstream its adoption. The integration of insect protein into mainstream livestock feed systems is not only a technical innovation but also a strategic move toward achieving environmental goals, enhancing food

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security, and building resilient food systems for the future. With appropriate investment, research, and cross-sector collaboration, insect protein can play a central role in the future of sustainable animal agriculture.

Nutritional Composition and Digestibility

Insect meals are nutritionally rich and well-suited to the dietary needs of livestock species. Crude protein levels typically range from 35–70%, while lipid content varies between 10–35%, depending on species, substrate, and processing technique [9]. Black soldier fly larvae (BSFL) are especially rich in essential amino acids, such as lysine, threonine, and methionine, and contain antimicrobial fatty acids like lauric acid, which support gut health [10]. Mealworms offer high digestible energy due to their lipid profile, and crickets provide a balanced composition of protein, fats, and minerals like calcium, magnesium, and iron [11].

Digestibility studies show insect protein to be on par with or superior to traditional feed sources. For instance, protein digestibility of BSFL in poultry ranges from 82–89%, while in pigs, it can reach up to 91%, depending on particle size and defatting. Mealworms show slightly higher lipid digestibility, making them ideal for energy-dense diets. The digestibility is also influenced by the presence of chitin, a fiber-like component of the exoskeleton. While chitin may reduce nutrient absorption in monogastric animals, moderate levels can act as prebiotics and improve intestinal health [12].

Advances in processing, including drying, enzymatic hydrolysis, and fermentation, have enhanced the nutritional value and reduced anti-nutritional factors in insect meals. For example, fermentation of BSFL improves amino acid availability and suppresses pathogenic microbes, making it safer and more efficient as a feed ingredient [13]. Studies are also exploring the use of microbial treatments to partially break down chitin, improving digestibility and reducing the need for synthetic additives in feed formulations. Overall, insect meals provide an excellent balance of macro and micronutrients and offer flexibility across feed formulations. They present a viable alternative to fishmeal and soy for inclusion in balanced livestock rations [14].

Performance Outcomes in Livestock

The application of insect-based protein in livestock diets has been extensively tested across a variety of animal species, including poultry, swine, and aquaculture. These trials demonstrate that insect meals can not only match but, in many cases, exceed the performance metrics achieved with conventional protein sources such as soybean meal and fishmeal.

- **Poultry:** In broiler chickens, partial replacement of soybean meal with BSFL meal (ranging from 10–30%) has led to comparable or improved growth performance, carcass yield, and feed conversion ratios (FCR). For instance, studies have shown that diets containing 20% BSFL meal resulted in FCR improvements of up to 5% and enhanced protein deposition in muscle tissue. Additionally, insect meals support gut health by modulating the intestinal microbiota and enhancing villus morphology. In laying hens, inclusion of BSFL or cricket meal improved egg yolk pigmentation, shell strength, and albumen height, reflecting better internal egg quality. Furthermore, the presence of antimicrobial peptides and lauric acid in BSFL helps to reduce pathogenic load in the gut, reducing dependence on antibiotic growth promoters [15].
- **Swine:** In pig diets, especially during the weaning and grower phases, insect protein has shown positive effects on performance and gut development. Inclusion of BSFL or mealworm meal up to 15% in weaning pig diets has led to increased average daily gain (ADG), improved nutrient digestibility, and reduced incidence of diarrhea. Some studies indicate that BSFL meal promotes a better gut barrier function, indicated by increased villus height and goblet cell numbers. The reduction in fecal ammonia and other nitrogenous waste also points to improved nutrient utilization, supporting both animal health and environmental outcomes. Furthermore, piglets fed diets containing insect meal have shown enhanced immunity, with elevated levels of immunoglobulins and reduced pro-inflammatory cytokines [16].
- **Aquaculture:** The use of insect protein in aquafeeds has gained substantial traction, especially in replacing fishmeal. In species like tilapia, rainbow trout, Atlantic salmon, and shrimp, inclusion of BSFL meal at levels up to 50–75% has maintained or improved growth performance, feed efficiency, and survival rates. Crickets and mealworms have also been tested with positive outcomes. BSFL oil, a by-product of protein extraction, provides essential fatty acids that support immune response and stress tolerance in fish. Importantly, these insect-based diets have not adversely affected fillet quality, taste, or consumer acceptance, making them suitable for commercial aquaculture operations [17].
- **Other Livestock:** Preliminary studies in ruminants (e.g., goats and cattle) suggest that insects can supplement protein requirements in forage-deficient systems, though more research is needed to assess rumen compatibility. Additionally, rabbits and companion animals like dogs and cats have been shown to tolerate insect-based diets well, opening further avenues for use [18].

The insect protein performs well across livestock categories, supporting not just productivity but also animal health and welfare. These consistent results highlight its commercial viability and justify broader integration into modern feeding strategies.

Environmental and Economic Benefits

One of the strongest cases for adopting insect-based proteins in animal feed lies in their substantial environmental benefits compared to traditional feedstocks like soybean meal and fishmeal. Insect farming requires far less land and water, generates fewer greenhouse gas emissions, and offers opportunities for recycling organic waste that would otherwise contribute to landfills or methane emissions.

- **Environmental Advantages:** Life cycle assessments (LCA) show that black soldier fly larvae (BSFL) protein

https://doi.org/10.61577/jalf.2025.100003

production emits up to 80% fewer greenhouse gases than soybean cultivation and fishmeal processing. A kilogram of protein from BSFL uses as little as 2 square meters of land, compared to 60 square meters for soy. Insects can also be cultivated on a wide range of organic substrates—including food scraps, agricultural residues, brewery waste, and animal manure—offering a highly efficient bioconversion system. This contributes to a circular economy where waste becomes a resource [19]. Furthermore, BSFL compost residue (called frass) is a valuable biofertilizer rich in nitrogen, phosphorus, and beneficial microbes, supporting sustainable crop production. When integrated into mixed farming systems, insect farms can close nutrient loops, minimize external inputs, and promote holistic agroecological practices.

- **Economic Feasibility:** Despite high potential, insect meal remains more expensive than conventional feed protein sources, with prices currently ranging between $1.5–2.0 per kg compared to $0.5–0.7 for soybean meal. However, operational scaling, automation, and policy support are steadily reducing costs. Companies across Europe, Asia, and Africa are investing in automated vertical farming systems that enhance productivity and lower labor demands [20]. Innovations in substrate optimization (e.g., using consistent food processing by-products) and genetic improvement of insect strains are also improving feed conversion efficiency and protein yields. Moreover, as pressure mounts to decarbonize supply chains, the environmental credentials of insect protein are likely to attract green investment, carbon credits, and sustainability-driven procurement policies [21].

From a local development perspective, insect farming offers additional socio-economic benefits. It enables decentralized, small-to-medium-scale operations that create rural jobs, empower women and youth, and build climate-resilient income streams [22]. In regions where traditional protein feed sources are expensive or imported, local insect production enhances feed security and price stability. The insect farming aligns with key environmental, economic, and social goals. It reduces the ecological footprint of animal agriculture, offers market differentiation for environmentally conscious producers, and paves the way for resilient, decentralized, and inclusive agri-food systems [23].

Conclusions

Insect-based protein represents a forward-looking solution to the environmental, nutritional, and economic challenges facing the global livestock sector. With high protein content, favorable amino acid profiles, and beneficial lipids, insect meals particularly from black soldier fly larvae, mealworms, and crickets offer a nutritionally viable alternative to conventional feeds such as soybean meal and fishmeal. Feeding trials across poultry, swine, and aquaculture species demonstrate consistent improvements in growth, feed efficiency, immunity, and gut health, further strengthening the case for their adoption.

From an ecological standpoint, insect farming significantly reduces the environmental footprint of feed production, offering a circular approach that transforms waste streams into valuable protein and fertilizer. Economically, although production costs remain a limiting factor, trends in automation, regulation, and investment indicate that price competitiveness is achievable in the near future. Furthermore, insect agriculture supports inclusive development, rural livelihoods, and decentralized food systems. To fully realize the potential of insect-based feeds, coordinated efforts are required from researchers, policymakers, industry leaders, and producers. Regulatory harmonization, public education, safety standards, and incentives for innovation will be essential to accelerate adoption at scale. In conclusion, integrating insect protein into animal nutrition is not merely an option but a necessary step toward more sustainable, resilient, and regenerative livestock farming.

Acknowledgment

The authors extend their sincere gratitude to colleagues for their guidance and support throughout this research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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