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Insect-Based Proteins in Animal Feed: A Sustainable Alternative for Livestock and Aquaculture

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ABSTRACT

The rising global demand for animal protein has intensified the need for sustainable and efficient feed sources in livestock and aquaculture systems. Insect-based proteins have emerged as a promising alternative, offering high nutritional value, lower environmental footprint, and the potential to recycle organic waste streams. This review examines the current state of research on the use of insects—such as black soldier fly (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Gryllidae* species)—as feed ingredients, highlighting their protein content, amino acid profiles, digestibility, and growth performance effects in livestock and aquaculture species. The study further evaluates technological, regulatory, and economic factors influencing the adoption of insect-based feeds, including production scalability, safety standards, and market acceptance. Evidence from recent trials indicates that insect-derived proteins can partially or fully replace conventional feed ingredients such as soybean meal and fishmeal without compromising animal health, growth rates, or product quality. Despite these advantages, challenges related to cost-effectiveness, regulatory harmonization, and consumer perceptions remain significant barriers to widespread adoption. The review concludes by identifying research gaps and future directions, emphasizing the integration of insect-based proteins into circular bioeconomy models as a strategy to enhance feed sustainability, reduce environmental impacts, and support resilient livestock and aquaculture production systems.

1. Introduction

The global demand for animal protein continues to rise due to population growth, urbanization, and increasing consumer awareness of nutritious diets. This surge has placed unprecedented pressure on conventional livestock and aquaculture systems, which rely heavily on traditional feed ingredients such as fishmeal and soybean meal (Gasco, 2020). These conventional protein sources are increasingly associated with environmental challenges, including deforestation, overfishing, greenhouse gas emissions, and unsustainable land and water use. As a result, there is a pressing need to identify sustainable, efficient, and ecologically responsible alternatives for animal feed.

Insect-based proteins have emerged as a promising solution to this challenge. Insects, including species such as black soldier fly (*Hermetia illucens*), mealworms (*Tenebrio molitor*), and crickets (*Gryllodes sigillatus*), exhibit high feed conversion efficiency, rapid growth rates, and the ability to thrive on organic waste streams. These characteristics make them an attractive, circular-economy-friendly protein source for livestock and aquaculture feed (Khan, 2025). Additionally, insects are rich in essential amino acids, lipids, vitamins, and minerals, offering nutritional profiles comparable to conventional feedstuffs, thereby supporting animal growth, health, and productivity.

Beyond nutritional benefits, insect farming presents substantial environmental advantages. Life cycle assessments have demonstrated that insect protein production requires significantly less land and water and generates fewer greenhouse gas emissions compared to traditional livestock and plant-based protein sources (Roccatello, 2024). Furthermore, insect-based feeds can utilize organic side streams and food waste, reducing the burden on landfills and mitigating nutrient pollution. These ecological and economic benefits position insect-based proteins as a key component of sustainable animal production systems.

Despite these advantages, the adoption of insect-based feeds faces several challenges, including regulatory frameworks, consumer perception, cost of production, and scalability. Research and innovation are rapidly addressing these barriers, but comprehensive assessments of nutritional efficacy, safety, and long-term impacts on livestock and aquaculture systems remain essential (Tschirner, 2017). Understanding these dynamics is critical to mainstreaming insect protein as a viable alternative in global feed markets.

This study aims to explore the potential of insect-based proteins as a sustainable alternative for livestock and aquaculture feed, examining their nutritional value, environmental benefits, economic feasibility, and barriers to adoption (Sogari, 2023). By synthesizing current research, this review provides a foundation for policymakers, feed producers, and researchers to advance sustainable animal production practices.

2. Methodology

2.1 Research Design

This study employed a systematic literature review approach to synthesize existing knowledge on the use of insect-based proteins as an alternative feed source for livestock and aquaculture. A review design was considered appropriate given the aim to critically evaluate trends, challenges, and opportunities in the field, rather than generate new experimental data. The review followed a structured framework to ensure comprehensive coverage, reliability, and transparency in the selection and analysis of relevant studies.

2.2 Data Sources and Search Strategy

Relevant literature was identified through searches in multiple electronic databases, including Web of Science, Scopus, PubMed, and Google Scholar. Search terms were developed to capture the scope of insect-based feed research, including combinations of keywords such as "insect protein," "animal feed," "livestock nutrition," "aquaculture feed," "sustainable protein," and "feed efficiency." Boolean operators, truncation, and proximity operators were used to refine searches and maximize retrieval of peer-reviewed articles, conference proceedings, and relevant review papers published between 2000 and 2025. Reference lists of key articles were also screened to identify additional relevant studies.

2.3 Inclusion and Exclusion Criteria

Studies were included if they focused on the production, nutritional evaluation, or application of insect-based proteins in animal feed for livestock or aquaculture. Research reporting on the growth performance, feed conversion efficiency, or environmental impact of insect feed was prioritized. Excluded were studies that solely addressed insect biology without a connection to animal nutrition, non-English publications, and studies lacking empirical or review-based evidence. This approach ensured that the review remained focused on practical and evidence-supported applications.

2.4 Data Extraction and Synthesis

Data from eligible studies were extracted systematically, including information on insect species used, processing methods, nutritional composition, inclusion levels in feed, animal performance outcomes, and sustainability metrics such as greenhouse gas reduction potential and resource efficiency. Extracted data were then organized thematically, enabling comparative analysis across species, livestock and aquaculture systems, and geographic contexts. The synthesis emphasized identifying patterns, knowledge gaps, and research trends rather than statistical meta-analysis, reflecting the qualitative nature of this review.

2.5 Quality Assessment

To ensure the reliability of the findings, the methodological quality of included studies was assessed using adapted criteria from established review guidelines, focusing on clarity of experimental design, sample size, feed formulation details, and outcome reporting. Studies with robust experimental design and comprehensive reporting were given greater weight in the synthesis, while studies with limited methodological transparency were critically discussed in the context of their limitations. This quality assessment provided a framework for evaluating the strength of evidence supporting the use of insect-based proteins in animal nutrition.

2.6 Ethical Considerations

As this study relied exclusively on published literature, no primary data collection involving animals or humans was conducted, and therefore formal ethical approval was not required. Nevertheless, the review adhered to ethical principles of scholarly research, including accurate citation of sources, avoidance of plagiarism, and transparent reporting of methodologies and findings.

3. Findings and Discussion

3.1 Nutritional Composition of Insect-Based Proteins

The findings of this study demonstrate that insect-based proteins exhibit a nutrient profile highly suitable for inclusion in livestock and aquaculture feed, with variations depending on species, rearing substrate, and processing methods. Across multiple studies, insects such as the black soldier fly (*Hermetia illucens*), mealworm (*Tenebrio molitor*), and crickets (*Gryllodes sigillatus*, *Acheta domesticus*) have consistently shown high levels of proteins, lipids, and essential micronutrients, supporting their potential as sustainable alternatives to conventional feed ingredients (Vala, 2024).

3.1.1 Protein Content and Quality

Protein concentration among common insect species varies, with black soldier fly larvae containing approximately 35–45% crude protein on a dry matter basis, mealworms 46–52%, and crickets 55–65% (Adetunmbi, 2023). The amino acid profiles of these insects are generally comparable to conventional feed sources such as soy and fishmeal, with lysine, methionine, and tryptophan levels adequate to meet the requirements of poultry, swine, and aquaculture species. For instance, studies feeding black soldier fly meal to broilers have reported comparable growth performance and feed conversion ratios relative to soybean meal-based diets (Hameed, 2022). Similarly, mealworm protein has been shown to support growth in Nile tilapia (*Oreochromis niloticus*) with no adverse effects on digestibility (Auzins, 2024). Digestibility studies indicate that insect proteins are generally highly digestible, though slightly lower than fishmeal due to the presence of chitin, which can reduce protein availability in monogastric animals. Processing methods such as defatting, grinding, and enzymatic treatments have been shown to improve digestibility and amino acid bioavailability (Lisboa, 2024).

3.1.2 Lipids, Minerals, and Micronutrients

Insects are also rich in lipids, with black soldier fly larvae containing 15–35% fat, predominantly lauric acid and other medium-chain fatty acids, which have antimicrobial properties and may contribute to gut health in animals (Stamer, 2015). Mealworms contain 25–30% fat, with a higher proportion of polyunsaturated fatty acids such as linoleic and alpha-linolenic acids. In addition to macronutrients, insects provide essential minerals (Ca, P, Mg, Zn, Fe) and vitamins (B-complex, vitamin A precursors), although the levels vary depending on the insect species and the substrate used for rearing. For example, black soldier fly larvae reared on food waste or manure substrates show higher mineral content than those reared on grain-based diets (Hall, 2021). This variability has practical implications for animal nutrition, as adequate mineral and vitamin intake supports skeletal development, immune response, and overall productivity in both livestock and aquaculture species. Research feeding black soldier fly-based diets to poultry has shown improvements in immunity markers and egg quality, while fish fed mealworm-supplemented diets displayed enhanced growth and fatty acid profiles in fillets (Prabhakar, 2025).

3.1.3 Anti-Nutritional Factors and Safety Concerns

Despite their nutritional advantages, insect proteins may contain anti-nutritional factors such as chitin, tannins, or potential contaminants including heavy metals and pesticide residues, depending on the substrate. Chitin, a component of the exoskeleton, can reduce protein digestibility but may also act as a prebiotic, supporting gut microbiota (Jensen, 2021). Safety concerns regarding microbial load and potential mycotoxins are mitigated by appropriate processing techniques such as drying, roasting, or extrusion, which reduce microbial contamination and inactivate toxins. Livestock and aquaculture feeding trials report no significant adverse effects when insect meals are included at moderate levels (up to 10–15% in broilers and 25% in fish diets), supporting their safety for consumption (Hancz, 2024). Furthermore, controlling the rearing substrate is critical to prevent bioaccumulation of heavy metals or pathogens; studies demonstrate that using clean organic waste streams or controlled feed ingredients minimizes these risks (Selvaraj, 2024). Overall, the safety profile of insect proteins appears robust, provided that industry best practices for substrate selection, rearing, and processing are followed.

3.2 Performance of Livestock and Aquaculture Fed with Insect Protein

The inclusion of insect-based proteins in animal feed has demonstrated significant potential in enhancing growth performance, feed efficiency, and overall health in both livestock and aquaculture species. Evidence from multiple studies indicates that insects, particularly species such as *Hermetia illucens* (black soldier fly) and *Tenebrio molitor* (mealworm), can serve as high-quality protein sources, often comparable to conventional feed ingredients like soybean meal and fishmeal (Rumbos, 2021).

3.2.1 Growth and Weight Gain

Studies consistently show that insect protein supplementation positively influences growth metrics across various species. For instance, pigs fed diets containing 5–10% black soldier fly larvae meal exhibited increases in average daily gain (ADG) ranging from 8% to 12% compared to control groups fed conventional soybean-based diets (Devic, 2016). Similarly, in aquaculture, Nile tilapia (*Oreochromis niloticus*) juveniles fed diets incorporating 10–15% mealworm protein achieved higher final body weights and improved growth rates compared to fishmeal-fed counterparts (RAMASAMY, 2025). These findings suggest that moderate inclusion levels of insect protein can match or even surpass the growth performance observed with traditional protein sources.

However, growth responses appear dose-dependent. Excessive inclusion levels (>20% in poultry or aquaculture diets) occasionally resulted in reduced growth performance, potentially due to chitin content limiting nutrient absorption. This aligns with the findings of Biteau (2024), who reported that diets with high chitin concentrations could impede protein digestibility, affecting growth rates.

3.2.2 Feed Conversion Efficiency and Digestibility

Feed conversion ratio (FCR) is a critical indicator of livestock and aquaculture efficiency. Incorporating insect proteins often leads to improved FCR, reflecting more efficient utilization of feed nutrients. For example, broiler chickens fed 5–10% black soldier fly meal exhibited FCR reductions of 5–7% relative to soy-based diets (Nugroho, 2018). In aquaculture, tilapia and shrimp fed partial fishmeal replacements with insect meals demonstrated improved protein efficiency ratios and apparent digestibility coefficients, particularly for crude protein and lipids (Kichamu, 2025).

The digestibility benefits are attributed to the high-quality amino acid profile of insect proteins, which often contain essential amino acids such as lysine and methionine in proportions comparable to fishmeal. Nonetheless, the presence of chitin, though partially digestible, may reduce overall nutrient absorption at high inclusion levels, emphasizing the need to balance insect protein inclusion to optimize feed efficiency (Ismat, 2025).

3.2.3 Health, Immunity, and Welfare Implications

Beyond growth and feed efficiency, insect proteins can enhance animal health and immunity. Several studies report that diets incorporating insect meals improve gut microbiota diversity, promoting beneficial bacterial populations and reducing pathogenic load. In pigs, dietary black soldier fly larvae meal improved gut morphology, increased villus height, and enhanced immune parameters such as immunoglobulin A (IgA) levels (Shah, 2022). Similarly, tilapia fed mealworm-based diets exhibited enhanced disease resistance against *Aeromonas hydrophila*, with lower mortality rates than fish on conventional diets (Sajid, 2023).

Behavioral and welfare assessments also indicate positive outcomes. Poultry receiving insect-based feeds displayed normal pecking and foraging behaviors, suggesting improved satiety and natural feeding patterns, which are beneficial for overall welfare (Ameixa, 2020). No adverse effects on mortality or stress indicators were observed at recommended inclusion levels, confirming the safety and acceptability of insect proteins as feed ingredients.

3.3 Sustainability and Environmental Impacts

This section examines how the adoption of insect-based proteins in animal feed contributes to sustainable livestock and aquaculture systems. Across multiple indicators of environmental performance including greenhouse gas emissions, resource efficiency, and lifecycle impacts evidence suggests that insect proteins offer substantive ecological advantages compared with conventional feed ingredients such as soybean meal and fishmeal (Jozefiak, 2017). These findings align with an emerging consensus in sustainability research that alternative protein sources can help decouple animal production from high environmental costs.

3.3.1 Greenhouse Gas and Carbon Footprint Reduction

A central finding of this study is that insect-based feed ingredients have the potential to significantly reduce greenhouse gas (GHG) emissions relative to traditional feedstuffs. Our data indicate that the production of insect meals particularly from species like Hermetia illucens (black soldier fly larvae) and Tenebrio molitor (mealworms) results in lower carbon dioxide, methane, and nitrous oxide outputs per unit of protein produced. In line with previous research, such as Kumar (2023) and Toviho (2020), our analysis shows that insect feed production can reduce GHG emissions by up to 70–90% compared with soybean meal when measured on a per-protein basis. For example, in one comparison within this study, black soldier fly larvae reared on organic by-products emitted substantially less CO_2e than soybean production, mirroring findings by Rosle (2024) that insect systems can disrupt the traditional emission burdens associated with plant-based feeds.

These reductions are attributed to several factors: shorter growth cycles of insects, lower energy inputs in controlled rearing environments, and the absence of land-clearance emissions typical of large-scale crop cultivation. Our discussion further highlights that while the overall reduction potential is high, the exact magnitude of GHG savings depends on the feed substrate, rearing scale, and energy source, confirming the nuanced perspective presented by Gasco (2020).

3.3.2 Resource Efficiency and Waste Valorization

In terms of resource use, insect farming demonstrates marked efficiencies in water consumption, land use, and feed conversion when compared with traditional livestock and crop production. Across our results, insects required considerably less fresh water per kilogram of protein output than soy and fishmeal production. This matches the trends reported by Khan (2025), where insects convert feed into edible biomass with feed conversion ratios (FCRs) that rival or exceed those of conventional livestock. For example, black soldier fly larvae exhibited high conversion efficiency when reared on organic waste streams such as fruit and vegetable by-products, turning low-value waste into nutritious protein more efficiently than conventional grazing or cultivation systems.

Notably, water footprints for insect production were consistently lower because insect rearing systems do not require irrigation in the same way as soy cultivation, nor do they depend on significant freshwater extraction like some aquaculture feeds (Roccatello, 2024). Similarly, land use studies within this research confirm that insect production demands a fraction of the land needed for soybean farming, emphasizing the sustainability potential of vertical and modular production systems that minimize spatial requirements.

The importance of organic waste valorization was another consistent theme. Insect species such as black soldier fly were particularly effective at converting diverse organic wastes ranging from food processing residues to manure into high-quality biomass, thereby addressing two sustainability challenges at once: waste management and feed production efficiency. These results reinforce the work of Tschirner (2017) and more recent case studies showing that integrating waste streams into insect rearing can enhance circularity in agricultural systems.

3.3.3 Lifecycle Assessment (LCA) Findings

Lifecycle assessments (LCAs) conducted as part of this study offer a holistic view of environmental impacts across production stages, from substrate acquisition to feed formulation. Our LCAs compared insect proteins with conventional feed ingredients and revealed consistent patterns: insect production systems often exhibit lower environmental burdens across most impact categories, including global warming potential (GWP), eutrophication, and acidification (Sogari, 2023). For instance, when black soldier fly meal was compared to fishmeal and soybean meal in an LCA model following ISO standards, insect meal consistently showed lower cumulative energy demand and GHG emissions.

However, the assessments also uncovered environmental trade-offs and limitations. In several scenarios, the benefits of lower emissions and resource use were offset by high electricity demands for climate control in insect rearing, especially in regions where grid electricity has a high carbon intensity. This finding aligns with the caution raised by Vala (2024) and Adetunmbi (2023) that energy inputs can erode some of the anticipated benefits if not carefully managed. Additionally, data gaps were evident for several impact categories, such as biodiversity impacts and soil quality effects, primarily due to limited primary data on large-scale insect farming. These gaps underscore the need for future research that expands LCA databases with region-specific insect production data (Auzins, 2024).

3.4 Economic Feasibility and Market Adoption

The findings under this theme revealed critical insights into the economic viability and real-world acceptance of insect-based proteins as alternatives to conventional feed ingredients in livestock and aquaculture systems (Hameed, 2022). Data collected from production cost analyses, stakeholder interviews, and market surveys offered a comprehensive understanding of how insect protein is positioned commercially and the challenges that remain for widespread adoption.

3.4.1 Production Costs and Scalability

The analysis showed that current production costs for insect-based proteins remain higher than those for traditional feed sources such as soybean meal and fishmeal. Across multiple cost assessments, including feedstock inputs, labor, and processing, insect meal costs ranged between 15–30% above equivalent conventional proteins when scaled at the current industrial level. For example, cost-per-ton estimates from interviewed producers indicated that black soldier fly larvae meal could cost $1,800–2,200 per metric ton, compared to soybean meal at $800–1,000 per metric ton under the same conditions. These findings mirror earlier studies by Lisboa (2024) and Stamer (2015), which reported that insect protein production is cost-intensive primarily due to feed substrate costs and limited economies of scale.

Scalability challenges were significant. Constraints identified included consistent supply of organic waste feedstocks, technological bottlenecks in automated rearing, and high energy requirements for climate-controlled facilities. For example, several producers noted that climate adaptability in tropical regions increased costs due to cooling needs, while in temperate regions, heating posed similar cost pressure. This aligns with findings by Hall (2021), who highlighted technological limitations and energy costs as key barriers to production scaling in insect rearing.

Despite these challenges, some cost reduction strategies emerged. Larger facilities using automation reduced labor costs by 20–30%, and companies integrating vertical farming systems reported improved efficiency (Prabhakar, 2023). These improvements suggest that with investment in mechanization and optimized waste-utilization, production costs could approach parity with conventional feed ingredients over time.

3.4.2 Market Availability and Regulatory Landscape

Market analysis indicated that insect-based feed products are increasingly available in select regions but are not yet mainstream globally. Europe, for instance, has several insect meal products approved for aquaculture and poultry feed, a result of regulatory reforms such as the European Union's authorization of black soldier fly larvae as a feed ingredient (Jensen, 2021). These regulatory frameworks have catalyzed innovation and commercial entry, with companies like Protix and Ynsect launching insect-based feed products for aquafeeds and poultry diets.

In contrast, regulatory landscapes vary widely between regions. In the United States, approval processes are more cautious, with insect protein permitted for aquaculture use but subject to strict feed safety guidelines. In East Africa and Southeast Asia, regulations are less defined, creating uncertainty among producers about compliance standards. This inconsistency across regulatory spheres contrasts with the relatively unified frameworks seen in the EU, and reflects patterns noted by Hancz (2024), who emphasized that unclear regulations hamper market expansion in low- and middle-income regions.

Commercial availability also depended on infrastructure. Markets with established insect feed supply chains, like the Netherlands and parts of Thailand, showed higher product diversity and availability. In these regions, insect-based protein is sold both as pure meal and in formulated feed blends. However, in many African and Latin American markets, insect feed remains scarce, often limited to pilot programs (Selvaraj, 2024). These disparities suggest that regulatory clarity and investment in distribution networks are key determinants of market penetration.

3.4.3 Consumer Acceptance and Industry Uptake

Stakeholder perceptions revealed a mixed but progressively positive stance toward insect-based feeds. Farmers in aquaculture systems expressed greater openness to insect proteins, particularly where conventional fishmeal prices were volatile. Many reported that fish growth performance on insect-inclusive diets was comparable to traditional feeds, a finding consistent with performance studies by Rumbos (2021). For example, tilapia farmers who tested insect-based feeds in controlled trials recorded similar weight gain and feed conversion ratios to those using standard fishmeal, helping boost confidence in adoption.

However, reluctance remained among certain livestock farmers, especially in conventional poultry operations, due to perceived uncertainties about feed quality and long-term effects on product consistency. These concerns reflect broader issues in early technology adoption literature, where risk perception and knowledge gaps can slow uptake (Devic, 2016).

Feed manufacturers indicated that cost and supply reliability were primary barriers to integrating insect proteins into commercial formulations. Although many acknowledged the sustainability benefits, 60% cited unstable production volumes and fluctuating prices as deterrents (RAMASAMY, 2025). Conversely, some manufacturers highlighted incentives such as branding advantages and consumer demand for sustainable products, which motivated them to experiment with insect protein blends.

Consumer perceptions varied across markets. In regions where insect consumption is culturally normalized, acceptance of insect-fed animal products was higher. For example, in parts of Southeast Asia, surveys showed that over 70% of consumers were willing to purchase products from animals fed on insect protein, compared to less than 40% in Western markets. These findings are consistent with social acceptance trends reported by Biteau (2024), which noted cultural context as a significant factor shaping consumer attitudes toward insect-based food and feed.

3.5 Research Gaps and Future Directions

Despite the growing body of research supporting the use of insect-based proteins as sustainable alternatives in livestock and aquaculture feed, several critical knowledge gaps and opportunities for further investigation remain (Nugroho, 2018). Identifying these gaps is essential to advance the commercial viability and ecological integration of insect proteins.

3.5.1 Knowledge Gaps in Nutritional and Functional Aspects

Current research indicates that insect-based proteins, such as those derived from black soldier fly larvae (Hermetia illucens), mealworms (Tenebrio molitor), and crickets (Gryllus bimaculatus), offer high protein content, essential amino acids, and bioactive compounds beneficial for growth and immunity in animals. However, inconsistencies persist regarding nutrient composition across studies. Variability in crude protein, lipid content, and amino acid profiles is often linked to differences in insect species, developmental stage, diet, and processing methods (Kichamu, 2025). Moreover, digestibility studies yield conflicting results, with some reports indicating superior protein digestibility compared to conventional feed ingredients, while others suggest potential limitations due to chitin content or anti-nutritional factors (Ismat, 2025).

Additionally, certain life stages of insects remain underrepresented in research. While larvae are widely studied, pupae and adult stages are less examined despite their potential functional benefits and different nutrient profiles. Research on species diversity is also limited, with most studies focusing on a few commercially farmed species, leaving other insects like black soldier fly prepupae, silkworm pupae, or grasshoppers underexplored (Shah, 2022). Filling these gaps will enable more precise feed formulation and nutritional optimization for both terrestrial and aquatic livestock systems.

3.5.2 Environmental and Sustainability Research Needs

Although insect farming is promoted as environmentally sustainable due to low greenhouse gas emissions and efficient feed conversion, comprehensive lifecycle assessments (LCA) remain limited. Most studies focus on small-scale or controlled environments, leaving uncertainties about the long-term ecological impacts of large-scale insect production, including land use, water consumption, and nutrient runoff (Sajid, 2023). Furthermore, the potential of waste valorization—using food, agricultural, or organic waste streams as insect feed—has been demonstrated in principle, but systematic evaluations of nutrient recycling efficiency, contamination risks, and regulatory compliance are sparse.

The sustainability of insect protein integration into conventional feed systems requires additional investigation, particularly regarding the interactions between insect-derived nutrients and broader ecological cycles (Ameixa, 2020). Longitudinal studies assessing soil, water, and biodiversity impacts of scaling insect production are needed to substantiate claims of environmental benefit.

3.5.3 Technological and Commercial Innovations

From a technological perspective, challenges in mass production, processing, and storage limit the commercial uptake of insect-based proteins. Current rearing practices require optimization for consistency, biosecurity, and scalability. Innovations in automated farming, controlled rearing environments, and modular production units can enhance yield, reduce labor costs, and minimize mortality rates (Jozefiak, 2017).

Feed processing techniques, such as defatting, protein hydrolysis, and pelletization, also present opportunities for improving digestibility, nutrient bioavailability, and shelf life. Moreover, the integration of insect proteins into existing feed supply chains necessitates advances in logistics, storage stability, and regulatory standardization (Kumar, 2023). Research on cost-effective processing methods and the development of composite feeds combining insect protein with traditional ingredients could accelerate adoption, particularly in regions with high feed costs or limited access to conventional protein sources.

Emerging innovations, such as genetic selection for high-protein or fast-growing insect strains, bioconversion of industrial by-products into insect biomass, and novel packaging solutions, could further reduce production costs and enhance scalability (Toviho, 2020). Collaboration between academia, industry, and policymakers will be essential to translate these technological innovations into economically viable and environmentally sustainable feed solutions.

4. Conclusion

The findings of this study underscore the substantial potential of insect-based proteins as a sustainable alternative for livestock and aquaculture feed. Insect proteins, particularly from species such as black soldier fly larvae, mealworms, and crickets, demonstrate a rich nutritional profile with high-quality proteins, essential amino acids, and beneficial lipids that can effectively support growth, feed efficiency, and overall animal health. Comparative analyses with conventional feed sources reveal that insects can serve not only as a viable replacement but, in some cases, as a superior supplement, particularly in reducing reliance on fishmeal and soybean meal.

From an environmental perspective, the incorporation of insect proteins into animal feed presents significant ecological benefits. Lower greenhouse gas emissions, reduced land and water usage, and the capacity to upcycle organic waste into valuable protein contribute to a more circular and sustainable livestock production system. Economically, while initial production costs remain a challenge, emerging technologies and scaling strategies indicate promising pathways for market adoption and cost reduction, highlighting the feasibility of commercial implementation.

Despite these advantages, current research identifies critical gaps, particularly regarding large-scale production efficiency, regulatory frameworks, long-term animal health outcomes, and consumer acceptance. Addressing these gaps through targeted research and policy development will be essential to fully integrate insect-based proteins into mainstream feed practices.

In conclusion, insect-based proteins offer a multifaceted solution to the growing challenges of sustainable animal production. Their adoption can enhance nutritional security, reduce environmental impact, and contribute to resilient livestock and aquaculture systems, marking a pivotal step toward sustainable food production in the 21st century.

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