Circular Solutions in Poultry Nutrition: Insect Meal from Food Waste, Economic Feasibility and Consumer Insights

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Abstract

The escalating challenge of food waste and the environmental impact of conventional livestock feed production highlight the need for sustainable innovations in animal nutrition. Insects reared on food waste present a promising alternative to conventional plant-based proteins, such as soybean meal, in poultry diets. Species like black soldier flies, houseflies, and mealworms efficiently convert organic waste into high-protein biomass that supports poultry growth, productivity, and product quality. This approach reduces feed costs, adds value to waste streams, and contributes to a circular economy by closing nutrient loops and minimizing environmental burdens. Recent developments in insect farming technologies, including automation and optimized rearing systems, have enhanced the scalability, safety, and nutritional quality of insect-based feeds. However, consumer concerns regarding the use of food waste in insect production and the incorporation of insects in poultry feed may present barriers to adoption. Issues such as safety, food neophobia, and ethical considerations must be addressed through stakeholder education and transparent communication. Overall, using food waste to rear insects for poultry nutrition represents a novel and economically viable strategy to reduce reliance on conventional feed resources. Transforming food waste into insect meal for poultry nutrition offers a sustainable solution that supports a resilient and circular food system.

Keyword: Consumer, Economy, Food waste, Insect meal, Poultry production

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Introduction

Food loss and waste are significant threats to the sustainability of global food systems. According to the Food and Agriculture Organization of the United Nations (FAO), approximately one-third of food produced for human consumption, amounting to 1.3 billion tons annually, is either lost or wasted (FAO, 2011). One of the United Nations' Sustainable Development Goals (SDGs) aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030. Governments, policymakers, food industries, researchers, and non-governmental organizations have started collaborating to address this issue, implementing food policies that identify and quantify waste types to trigger a societal shift toward reducing food waste and its associated impacts (Kennard, 2020). Food waste can be classified into three categories as shown in Figure 1 (Ojha et al., 2020). Food waste disposal creates 8-10% of global greenhouse gas emissions, which mostly result from methane gas produced by landfill decomposition (UNEP, 2021).

The three main methods of food waste management consist of reduction, along with reusing and recycling (Sakai et al., 2011). The implementation of better processing, storage, and cooking methods leads to waste reductions. Food donation connections to hunger relief organizations are part of reusing activities, but recycling activities involve using food waste to feed livestock and generate energy through anaerobic digestion processes, as well as composting and bioenergy production systems (Thi et al., 2015). The use of insects for food waste bioconversion represents an emerging marketable solution to minimize food waste. Industrial insects demonstrate their capacity to transform large quantities of food waste into numerous valuable merchandise, extending from animal feed to fertilizers, biofuels, and secondary industrial substances (Fowles and Nansen, 2020). Many animals naturally consume insects as part of their diet, making them a valuable and sustainable ingredient for preparing animal feeds, particularly for poultry, fish, and pigs (Sogari et al., 2019). The production of insects uses minimal resources, including small land areas and water requirements, and shows a high efficiency in converting nutritional substrates (Fellows et al., 2014). Global feed producers have started to focus on insect proteins that can be used in animal feed products. Products from specific insect species now receive authorization through EU 2021/1372 for use in fish, poultry, and pig feeding regimes. Black soldier fly (BSF) derived products used in Canada and the United States follow different regulations between species according to Lähteenmäki-Uutela et al. (2021). The global insect meal supply stays limited because legislation restricts its availability, and production costs remain high, along with negative consumer perceptions toward insect-based animal feed (Gasco et al., 2021). The combination of larger production levels alongside technological improvements should enhance manufacturing capability and decrease related expenses (Lamsal et al., 2019). Insect proteins added to feed promote sustainability as they reduce reliance on soymeal and fishmeal resources while simultaneously rebirthing nutrient value from waste biomass (Smith and Barnes, 2015; van Huis et al., 2015). The psychological reactions of consumers to animal products from insect-fed animals remain unclear because research has not fully explored this topic. The acceptance of insect-fed foods depends on safety aspects and cultural preferences alongside considerations of pricing value (Dobermann et al., 2017; Imathiu, 2020). The analysis of existing literature regarding these consumer attitudes will support policy decisions and industrial plans to expand insect-based feed utilization.

This chapter investigates insect meal obtained from food waste as it presents both sustainability and cost-effective solutions for poultry nutrition. A thorough investigation of insect production practices exists, along with the study of regulatory guidelines and consumer acceptance trends, to demonstrate complete integration options of insect-based poultry feeds within circular economic systems.

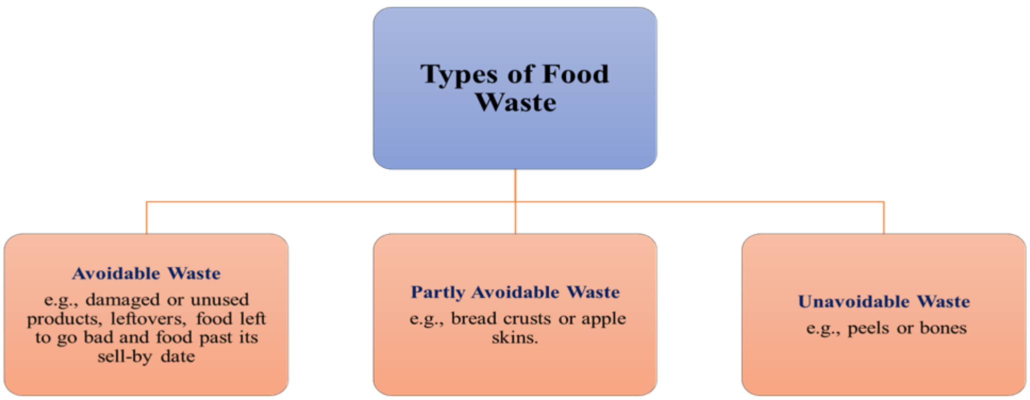

Fig. 1: Types of food waste

Food Waste for Mass Production of Insects

The four primary methods of insect production are xiroculture, hygroculture, aquaculture, and xyloculture, which may be perceived differently in terms of naturalness and risk (Grabowski et al., 2022). The commercial production of the black soldier fly (BSF) (*Hermetia illucens*) enables sustainable food waste management because it can convert waste materials into products consisting of animal feed, human food, and fertilizer. The black soldier fly operates with industry-level efficiency because its brief lifecycle enables speedy waste material breakage that results in valuable protein and oil biomass products (Matthäus et al., 2019). The bioconversion technology implemented by Agriprotein, Entosystem, Protix, and Goterra enables organizations to process 1.3 billion tons of yearly food waste, which yields profitable feeds for animals along with fertilizer and human food products. The Agriprotein daily process utilizes 350 tons of food waste to generate important end-products (Ojha et al., 2020). Food waste management depends on moisture content and nutritional composition, microbial contaminants, and non-organic contaminants. The housefly larvae need feeds that contain sufficient protein, yet BSF, together with mealworm larvae, receive nutrition from vegetative food waste according to Fowles and Nansen (2020). Meat-based waste serves as proper materials for both housefly and BSF feed according to Cheng et al. (2017). Homogenization and fermentation applied as pre-treatment methods by Law and Wein (2018) simultaneously enhance food safety and nutritional content and stabilize waste materials. Famous breeders need to thoroughly examine feed choices based on feeding behavior, immunity characteristics, and physical attributes. Temperature and humidity control through technological factors determine the rearing efficiency of BSF. Research on insect breeding continues to advance because it has shown potential to enhance bioconversion efficiency (Fowles and Nansen, 2020) while dealing with significant regulatory hurdles. EU regulations (EC, 2009) prevent farming insects with substrates that contain animal by-products or manure or any catering waste, as it must adhere to the standards for fed animals within the farming guidelines. International Platform of Insects for Food and Feed (IPIFF), as well as other advocacy groups, work towards reforming existing regulations to enable broader food waste use within insect production operations.

Research Endeavors to Transform Wasted Food into Insect Meal

Bioconversion efficiency or organic waste transformation refers to the extent to which nutrients in a substrate are converted into larval biomass (Bosch et al., 2020). Systems with high bioconversion efficiency are generally regarded as more sustainable in the long term (Parodi et al., 2020). The black soldier fly (BSF) is particularly effective at converting various types of food waste, including vegetable scraps, brewing industry by-products, and even carcass remnants, into nutrient-dense protein and fat. Importantly, BSF is neither a pest nor a vector of disease (Oonincx et al., 2015; Chia et al., 2018). Salomone et al. (2017) reported that up to 29.6 kg of dry BSF larvae can be produced from just one ton of food waste. This waste disposal technique reduces organic waste materials to small amounts. Insects convert wasted food into wholesome animal feed protein, resulting in both resource conservation and waste management at the same time (Salomone et al., 2017). The dual advantage of this method supports waste reduction along with global sustainability goals, and it enables sustainable feed production systems at the same time. Figure 2 illustrates food waste recycling to produce insects for poultry feed.

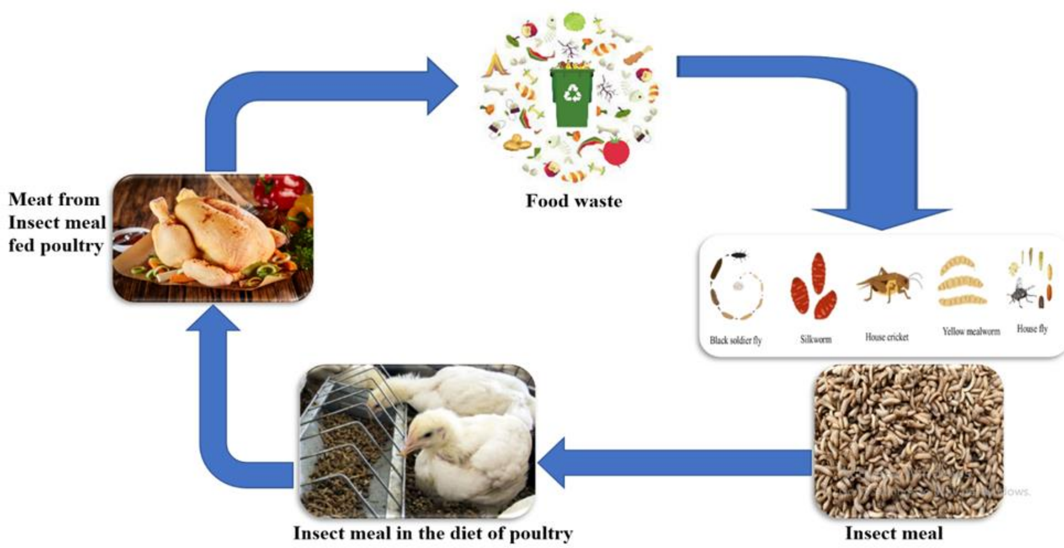

Fig. 2: Recycling food waste for the insect meal production and its use in poultry's diet

Importance of Insects in the Circular Economy

Unsustainable food production and consumption patterns require circular economy approaches in order to develop sustainable food systems (Jurgilevich et al., 2016). A "closing the loop" system integrates sustainability through the entire food process, starting from production and ending at processing, distribution, consumption, and waste management (Wunderlich and Martinez, 2018). Within the past ten years, the circular economy has gained popularity because it offers advantages across environmental domains, together with social and economic domains (Milios, 2018). A proven circular waste management solution transforms food waste into species larvae biomass that strengthens various sectors within the food industry. The ability of insects to transform organic waste into nutritious protein products depends on minimal resource needs and emits much lower amounts of greenhouse gases than traditional livestock systems (van Zanten et al., 2015). However, the expensive nature of insect meal acts as a major hurdle preventing its proper dissemination between manufacturers. Insect meal currently cost between $3,800 and $6,000 per ton, whereas fishmeal prices are between $1,400 and $1,800 per ton, and soybean meal comes at approximately $500 per ton (Biteau et al., 2024). Several factors render insect meal three to four times pricier than fishmeal while costing nine times as much as soybean meal. A key factor contributing to these high costs is the multiple conversion cycles involved: plants to insects, insects to livestock or fish, and finally to human consumption, which results in greater energy losses compared to direct plant-based feeding (van Huis, 2022). Additionally, the cost of insect production is heavily influenced by the price of substrates used as feed, particularly grain-based by-products, which also compete with the livestock industry (Halloran et al., 2017). Labor costs further impact operational expenses (Niyonsaba et al., 2023). To overcome these challenges, the strategic utilization of food waste as a substrate for insect meal production presents a viable solution. Given their high nutritional value and resource efficiency, insects play a crucial role in advancing sustainability and resource management in food production, making them a promising component of future food systems (Siddiqui et al., 2024). An example of income generation from the sale of insect meal produced from waste food is shown in Table 1.

Table 1: Income generation from the sale of insect meal produced from waste food

Country	Food waste (million tons)	Insect production (million tons) *	Income (billions$)**
USA	103 (FAO, 2023)	3.05	14.945
Europe Union	59 (Eurostat, 2024)	1.75	8.575
Turkiye	18 (FAO, 2021)	0.53	2.597
Pakistan	36 (Hilal, 2024)	1.07	5.243

*1 ton of food waste =29.6 kg of insect meal

**Insect meal can be sold for approximately $4,900 per ton (average of $3,800 and $6,000 per ton)

Bioactive Compounds in Food Waste

Food waste, primarily from perishable items like fruits, vegetables, and animal-based products, retains significant nutritional value despite losses during disposal (Wunderlich and Martinez, 2018). With a high moisture content (50–85%), processing techniques like heat treatment can improve its shelf life and safety for animal feed (Myer et al., 1999). Bioactive compounds in food waste, including polyunsaturated fatty acids (PUFA), vitamins, peptides, and polyphenols, provide health benefits. These compounds, particularly EPA, DHA, and arachidonic acid, are abundant in meat and fish waste, contributing to value-added livestock products (Pogorzelska-Nowicka et al., 2018; Georganas et al., 2020). Food waste crude protein (CP) content varies from 15–23% (dry basis), comparable to corn but lower than soybean meal (Myer et al., 2000). Ether extract (EE) content ranges from 17–24%, providing additional nutritional energy (Myer et al., 2000). Mineral and vitamin content in food waste depends on its source. Restaurant waste typically contains 3–6% minerals (ash) and varying vitamin levels, with animal-derived waste showing higher B-complex vitamins like riboflavin and B12, essential for poultry and swine nutrition (Myer et al., 2000; Georganas et al., 2020). Research highlights the potential of food waste for animal diets and value-added products, but variability in nutrient composition necessitates further investigation.

Nutritional Value of Insects

The utilization of insects is becoming widespread in different sectors, as they have high nutritional value with many proteins, fats, calcium, and bioactive compounds like chitin, antimicrobial peptides, and lauric acid. These constituents are known to be associated with beneficial effects on hematologic, biochemical, and immune functions (de Carvalho et al., 2020; Yazici and Ozer, 2021).

a. Chemical Composition of Insect Meal

Insects contain a key ingredient, protein, which makes up 23% to 76% of their dry matter content. The second most important component is fat, which is 20.0% (Zhou & Han, 2006; Rumpold & Schlüter, 2013). The protein quality of insects is high because of their amino acid composition. Insects' lipids are composed mainly of triacylglycerols (80%) and phospholipids (20%), where oleic acid (C18:1) is the major unsaturated fatty acid, whereas palmitic acid (C16:0) and stearic acid (C18:0) are the primary saturated fatty acids (Dossey et al., 2016). But insects provide little vitamin A, C, niacin, thiamine, and D, though they are rich in B vitamins, especially B12, riboflavin (B_2), and pantothenic acid (B_5) (Finke, 2002; Van Huis, 2013). The chemical composition of some insects has been given in Table 2.

Table 2: The average chemical composition of some insects compared to soybean meal (on a dry matter basis) (Janković et al., 2020; Belhadj Slimen et al., 2023; Khalifah et al., 2023).

Insect name	CP (%)	EE (%)	Methionine (%)*	Lysine (%)*	Ca (%)	P (%)
Black soldier fly (*Hermetia illucens*)	33-60.8	6.84-42.27	2.1	5.7	3.2	0.9
House fly (*Musca domestica*)	40.12-63.99	2.7-27.9	2.2	6.1	0.47	1.6
Locust (*Schistocerca gregaria*)	57.3	8.5	2.3	5.8	0.13	-
Mealworm (*Tenebrio molitor*)	27.15-53	3.6-38.3	1.5	5.4	0.27	0.78
Earthworm (*Eisenia fetida Lumbricus terresstris*)	41.42-65.68	2.25-18.5	0.96	3.33	1.46	0.80
Grasshopper (*Orthoptera*)	47.71	12.21	-	-	-	-
Silkworm (*Bombyx mori*)	45.87-71.9	2.5-30.3	3	7	0.38	0.60
Soybean meal (*Glycine max*)	44	0.9	0.65	2.95	0.32	0.65

CP: crude protein, EE: ether extract, Ca: calcium, P: phosphorous, * (% to 100% protein)

b. Bioactive Components in Insects

I. Chitin: Present in the exoskeletons of insects and crustaceans, chitin is the second most common polysaccharide that is recognized for its ability to enhance the immune system. Due to their biological and economic importance, chitin and its derivatives, chitosan and chito-oligosaccharides have gained significant attention. It promotes both innate and adaptive immune responses, exhibiting antibacterial, antifungal, and antiviral effects. Additionally, chitin hinders the growth of Gram-negative bacteria, such as *E. coli* and *Vibrio cholerae,* and *Bacteroides fragili* (Kipkoech et al., 2021; Khalifah et al., 2023).

II. Antimicrobial Peptides and Lauric Acid: Antimicrobial peptides (AMPs) sourced from insects have proven effective against antibiotic-resistant bacteria. These peptides demonstrate qualities that are both bacteriostatic and bactericidal, enhancing gut health, growth, and immune functions in livestock species like pigs and broilers. Another bioactive compound, lauric acid, showcases potent antiviral and antibacterial properties, especially targeting Gram-positive bacteria (Dierick et al., 2002; Khalifah et al., 2023).

Advantages of Incorporating Insect Meal in Poultry Feed

Insects offer a sustainable solution for converting low-value organic waste into high-quality proteins and fats. For free-ranging chickens, insects are a normal and necessary component of their diet. Insects are a rich source of proteins, AMP, chitin, and lauric acid, which make them a good source of protein and an alternative to antibiotics (Hwangbo et al., 2009; Van Huis, 2013). Research evidence shows insect meals as potential economic protein resources for poultry nutrition because they improve both developmental growth and feed efficiency ratios. Insects as an ingredient in poultry feed bring reduced environmental effects while decreasing the need for conventional protein sources (Sajid et al., 2023). The utilization of insects as animal feed protein could represent both a dependable source and a bountiful alternative compared to conventional feeds. Species of insects naturally supply protein to both fish populations and poultry species (Leiber et al., 2017). Insect meal functions as a promising protein feed ingredient for animal diets because of their nutritional content, thus scientists recognize it as a potentially sustainable approach (van Huis, 2022). Scientists evaluate insect meals as a suitable replacement for fish meal because their availability remains limited, especially for expanding aquaculture operations (van Huis, 2022. Research shows insect-based meals have the potential to achieve similar market standing as fish and SBM since these ingredients now dominate many aquaculture and animal feed formulations (Allegretti et al., 2018). Studies should evaluate current regulations on ration formulation to determine whether these microorganisms can be legally incorporated into livestock feed. Developing countries should increase meat consumption while also exploring alternative protein sources for animal feed. Several insect species offer high nutritional value, making them increasingly popular as preferred protein sources for animal feed.

The range of amino acid absorption by poultry from insect-based diets within the in vivo environment stands at 89–95% and matches relative values from FM (food meal). Housefly pupae showed similar protein and organic matter digestion patterns during *in vitro* tests, which were equal to results obtained from fish and poultry meals (Sajid et al., 2023). Young animals need insect-based protein consumption because their fast development period allows them to enhance their immune system strength. The black soldier fly protein derivative reduces free radical damage, which benefits livestock's body health. The aquatic life of these species often faces bacterial infections that lead to compromised immunity, accelerated aging, and other associated health threats (Lieke et al., 2020). Market-available insect-derived feeds enhance feed quality and digestibility to boost animal performance, together with improving safety and hygiene conditions and nutrient utilization in poultry production (Cheng et al., 2019).

Insects at all life stages are natural food for wild birds and poultry due to their desirable palatable nature (Zou et al., 2024). Artificial yellow mealworm and the three other insect types, including black mealworms (*Tenebrio obscurus*) and barley worms (*Zophobas morio*) alongside housefly larvae (*Musca domestica Linnaeus),* show potential as animal feed for chickens and other poultry breeds (Sánchez-Muros et al., 2014). The primary use of insect feeding occurs in broiler and laying hen breeding operations. Experiments demonstrated that yellow mealworms have the potential to act as a protein supplement for raising broilers since they increased body weight gain with enhanced economic benefits while maintaining broiler growth metrics (De Marco et al., 2015). Yellow mealworm has excellent potential to act as a protein supplement for raising broilers since it produces increased body weight gains with enhanced economic benefit while maintaining broiler growth metrics (Bovera et al., 2016). When YMWL serves as a laying hen feed, it meets their nutritional demands while lowering operational costs while delivering enhanced production numbers with no adverse effects on egg quality (Sedgh-Gooya et al., 2021).

Future Prospects of Insect Meal in Poultry Feed

Consumer views on insect farming methods are not well understood, with different rearing techniques influencing perceptions of safety and acceptability (Delwaide et al., 2015). Ethical concerns about insect slaughter, particularly pain perception and killing methods, remain unexplored (Van Huis et al., 2013). Cultural differences also play a key role in how insect-based foods and feeds are accepted, highlighting the need for research beyond Western perspectives (de Carvalho, 2020). Regulatory shifts and increasing consumer acceptance of alternative proteins also help open doors to more avenues for insect-based feeds (Sogari et al., 2019). The incorporation of insect meal with plant-based proteins can lead to more balanced diets, less reliance on conventional protein sources, and lower environmental impact (Park et al., 2022). Research is needed to understand the real potential of insect-based products in different poultry production systems. Insect farming businesses are still working towards maximizing efficiency, reducing production costs, and competing with traditional protein sources (Meyer-Rochow & Jung, 2020). The FAO supports the trend of using insects as an eco-friendly livestock feed; however, various and specific processing practices can affect nutritional quality and bioactivity of insect meal (Ojha et al., 2021).

Legislation, Food Safety, and Hazards Related to the Food-to-Food Production of Edible Insects

The world's nations implement different regulations for edible insects as food items and animal feed products. Prior to March 1997, edible insects did not exist in the EU market, so the European Food Safety Authority (EFSA) initially categorized them as 'novel foods' (Belluco et al., 2013). The EU market sales of these insects demand regulatory approval from the EFSA, the authorizing organization. Edible insects can be utilized as feed according to Regulation EU 999/2001 (EU, 2019). IPIFF states that livestock feed approval exists only for purified insect fat and hydrolyzed insect proteins, but non-hydrolyzed insect proteins can reach the market as pet food for fur animals (IPIFF, 2019). The EU regulation No 2017/893 establishes the authorized use of insect proteins obtained from seven species, including *Musca domestica* (Common Housefly), *Hermetia illucens* (Black Soldier Fly), *Tenebrio molitor* (Yellow Mealworm), *Alphitobius diaperinus* (Lesser Mealworm), *Acheta domesticus* (House Cricket), *Gryllodes sigillatus* (Banded Cricket), and *Gryllus assimilis* (Field Cricket) for aquaculture purposes (EU, 2019).

Food insect regulation within the United States follows a detailed and challenging procedure. The food industry in the United States receives regulatory oversight from two main bodies, comprising the Food and Drug Administration (FDA) with coordination support from the United States Department of Agriculture (USDA) alongside the Animal and Plant Health Inspection Service (APHIS) (Marone, 2016). All food products made from insects need to meet standard American food requirements by testing for *Salmonella* and *E. coli* and also require Food and Drug Administration authentication through the Federal Food, Drug, and Cosmetic Act (FFDCA) for Food Additives (GPO, 2019). Producers of edible insects need to satisfy every FDA requirement for manufacturing under Good Manufacturing Practice (GMP) standards (Halloran & Münke, 2014).

Canada considers insect-based foods to be novel foods, which creates complex regulations since the Food Inspection Agency (CFIA) under Health Canada sets food safety and public health standards, but the Food Directorate conducts novel food safety assessments (Halloran & Münke, 2014). The food safety regulations in Australia and New Zealand are established by Food Standards Australia New Zealand (FSANZ), which classifies edible insects as 'novel foods' (non-traditional foods) for assessment before commercialization unless directly forbidden for sale (Halloran & Münke, 2014; Marone, 2016). Thailand stands out as the most advanced and innovative nation in edible insect mass production, collection, processing, and transport and marketing, both for crickets and palm weevil larvae, and additional types like weaver ants, bamboo caterpillars, and grasshoppers, which are harvested from natural sources or collected seasonally (Hanboonsong et al., 2013). The large population, along with economic expansion in China, has not produced widespread edible insect mass production systems (Marone, 2016). The production chain of edible insects from farming through processing until distribution and consumption receives European African company collaboration in Africa (Halloran & Münke, 2014). Mass industrial edible insect food and feed production contains typical food chain risks that mainly derive from heavy metals, together with mycotoxins, pesticide residues, and pathogens (Van Huis, 2015). The food safety risks from insect-based food production manifest as two distinct hazards: those belonging to the species characteristics and the ones stemming from cultivation and manufacturing execution, as well as storage methods (ANSES, 2019).

Policy Considerations

To enhance consumer confidence in insect-based feed, clear policies such as labeling regulations should ensure transparency regarding quality and safety standards. Additionally, incentives for insect-based feed production could facilitate large-scale industrial development, reducing costs and increasing availability. Ethical guidelines must also be established to ensure the humane treatment of insects used in feed production, addressing potential concerns about their use as a sustainable protein source (Dentoni et al., 2023).

Conclusion

Utilizing insect meal sourced from food waste presents a sustainable and economically feasible substitute for traditional poultry feed. Its abundant nutritional content, comprising essential amino acids, beneficial fats, and bioactive compounds, bolsters poultry health while lessening dependence on conventional feed sources, i.e., soybean meal. Furthermore, insect farming fosters circular bioeconomy strategies by transforming waste materials into high-value feed components, thereby mitigating environmental repercussions. Nonetheless, the adoption of insect meal encounters challenges due to consumer hesitance, which is influenced by cultural norms, sensory perceptions, and labeling issues. To encourage acceptance, standardized labeling, transparent communication, and educational initiatives are imperative to enhance public perception and alleviate food neophobia. Regulatory frameworks must also ensure the safe, scalable, and cost-effective production of insect meal to expedite its incorporation into poultry nutrition.

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