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Insect Meal: A Future Prospect of Source of Protein and Trace Minerals in Practical Feeding of Pigs

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ABSTRACT

Increasing consumption of animal-derived foods is driving higher utilization of protein sources, especially soybean meal and fish meal, thereby straining feed availability. As a renewable resource, insects provide a rich supply of digestible protein, essential amino acids, and important minerals, making them a promising substitute for conventional feeds.Their production can be integrated into circular bio-economy systems through the use of organic waste streams, reducing both feed costs and environmental impact. Among the various insect species assessed, the silkworm pupae (*Bombyx mori*), housefly larvae (*Musca domestica*), yellow mealworm (*Tenebrio molitor*), and black army fly larvae (Hermetiaillucens) have demonstrated the most potential for inclusion in swine diets. Studies indicate that insect meals can support growth performance, nutrient utilization, immune response, and gut health, while also partially replacing conventional protein sources without compromising productivity. However, large-scale adoption is challenged by regulatory gaps, variation in nutrient profiles, consumer perception, and cost of mass production. Addressing these constraints through standardized processing, safety guidelines, and value-added innovations will determine the role of insects as a viable protein resource in practical pig feeding systems.

KEYWORDS: Insect meal, Micronutrients, Protein source, Sustainability, Swine nutrition.

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INTRODUCTION

Rapid demographic and socioeconomic changes are predicted to sharply elevate the consumption of meat and animal protein worldwide in the coming years (FAO, 2013). Pork remains the most consumed meat worldwide and will be a key contributor in addressing this demand. However, the livestock sector faces challenges in securing sustainable feed resources. Rising costs, competition with human diets, and ecological issues are reducing the sustainability of conventional protein feeds such as soybean meal and fishmeal (Henry et al., 2015; Makkar et al., 2014). This situation underlines the demand for alternative sources that balance nutritional adequacy with environmental sustainability.

Owing to their rich nutrient composition—characterized by quality protein, balanced amino acids, functional fats, and substantial concentrations of iron and zinc—edible insects are being explored as sustainable feed alternatives (Finke, 2002; Spranghers et al., 2017; Lu et al., 2022). These characteristics are especially relevant in pig production, where issues like iron-deficiency anaemia in piglets and zinc-dependent growth or health problems continue to be of concern. Furthermore, insect farming can be integrated into circular production systems, as insects can efficiently convert organic by-products and side streams into nutrient-dense biomass (Newton et al., 2005; Oonincx et al., 2015), thereby reducing reliance on conventional crops and lowering waste generation.

Despite their promise, the incorporation of insects into pig diets remains at a developmental stage. Knowledge gaps persist in areas such as nutrient digestibility, bioavailability of minerals, ideal inclusion rates, and long-term impacts on growth, health, and product quality (Biasato et al., 2019; DiGiacomo & Leury, 2019; Hong & Kim, 2022; Ringseis et al., 2021; Yoo et al., 2019). In addition, factors including consumer acceptance, safety considerations, regulatory constraints, and production costs influence their adoption on a commercial scale (Garofalo et al., 2019; Makkar et al., 2014).

Insects as Feed Resources for Pigs

Common Insect Species for Pig Nutrition

Several insect species have been investigated as feed resources for pigs, and studies reveal marked differences in their nutrient profile, digestibility, and ease of mass production (Biasato et al., 2019; Makkar et al., 2014). Among them, certain species have gained greater attention due to their ease of mass production, high protein content, and established safety profile. Insects considered for animal feeding are generally grouped into several taxonomic orders: Diptera (e.g., black soldier fly, housefly) Coleoptera (e.g., mealworm), Megadrilacea (e.g., earthworms), Lepidoptera (e.g., silkworm), and Orthoptera (e.g., grasshoppers, locusts, crickets) (Oonincx et al., 2015). These species have been identified as practical and resource-efficient replacements for commonly used protein feeds, offering a cost-effective option for animal production (Hong et al., 2022). Beyond their substantial protein contribution, insects also supply essential minerals and bioactive molecules, which add further value to their role in pig nutrition (Spranghers et al., 2017).

1. Black Soldier Fly (*Hermetiaillucens*)

Considering the diversity of insects assessed as potential feed ingredients,feed applications, the black soldier fly (BSF) has received the greatest research attention in animal nutrition.The larvae are capable of transforming food scraps and other organic residues into a nutrient-dense, protein-rich biomass. BSF larvae meal contains 40–45% crude protein and 30–35% fat, with favorable levels of lysine and methionine (Makkar et al., 2014). The fat fraction is particularly rich in lauric acid, which possesses antimicrobial properties (Spranghers et al., 2017). The digestibility of BSF protein in pigs has been reported to be comparable to soybean meal, making it a promising alternative feed ingredient (Cullere et al., 2016). One study reported that iron and zinc content of larvae was 1.4 mg per kg DM and 108 mg/kg DM respectively (Arango Gutiérrez et al., 2004).

2. Housefly (*Musca domestica*)

Their nutrient profile typically includes 40–60% crude protein and 15–20% fat, while the essential amino acid composition closely resembles that of fishmeal (Finke, 2002; Makkar et al., 2014). Their rapid life cycle and ability to grow on diverse substrates enhance feasibility for mass rearing. Incorporation of housefly larvae meal in pig diets, even at levels displacing nearly half of standard protein meals, has not been associated with negative growth responses (DiGiacomo & Leury, 2019; Hong & Kim, 2022).

3. Mealworm larvae (*Tenebrio molitor)*

Mealworms are widely studied within the Coleoptera order. Nutrient analyses show that insect larvae typically provide a high protein content, ranging from about 45–55%, along with lipid levels that may reach nearly 30% heir amino acid composition, particularly in sulfur-containing amino acids, is favorable for monogastric animals (Spranghers et al., 2017; Lu et al., 2022). The lipid profile of mealworms, dominated by unsaturated fatty acids, has the potential to affect fat deposition characteristics in swine. Large-scale rearing is feasible under controlled conditions, although costs remain higher than BSF (Oonincx et al., 2015). While mealworms consume a wide variety of foods in nature, rearing practices commonly employ wheat bran or flour as a base substrate, sometimes enhanced with protein-rich additives like soybean meal, yeast, or skimmed milk powder (Makkar et al., 2014). Their larvae provide a valuable source of trace minerals, with reported concentrations of iron (≈66.9 mg/kg) and zinc (≈104.3 mg/kg) (Spranghers et al., 2017).

4.Earthworm (*Eisenia fetida* and others)

Earthworms, belonging to Megadrilacea, have long been evaluated as unconventional protein sources. The nutrient profile often ranges from 55–65% digestible protein, accompanied by appreciable amounts of calcium, magnesium, and iron. However, large-scale production remains challenging due to slow growth and rearing difficulties (Ijaiya and Eko, 2009). Limited feeding trials in pigs indicate potential as a supplementary protein source (Biasato et al., 2019). Unlike earthworms that ingest soil together with organic matter, epigeic types feed solely on organic substrates. Their meal provides about 63% protein, making it a potential protein supplement for monogastric animal diets. Apart from its higher protein content it is also rich source of iron

(1050–2990 mg/kg) and could be the possible source of iron supplementation in the diet of pigs (Spranghers et al., 2017).

5. Grasshoppers *(Locusta migratoria)*

Natural settings such paddocks, ponds, croplands, and meadows are good places to gather grasshoppers (GH) (Khusro et al., 2012). Utilizing these insects as feed not only provides a sustainable protein source but also helps in reducing dependence on chemical pesticides for their control. In this way, insects that are otherwise considered pests can be converted into a valuable and low-cost protein supplement for poultry diets, particularly in resource-limited regions. Grasshopper meal is a good source of protein (29 to 77.1%) and particularly rich source of Zn (17.34 mg/100 g DM) and Fe (16.19 mg/100 g DM)) possible a better alternative of protein with additional advantage of higher iron and zinc content in the diet of pigs (Makkar et al., 2014, Newton et al., 2005).

6. Locust (*Schistocerca gregaria*)

Locusts, often described as desert locusts, migratory locusts, brown locusts, or red locusts, are utilized in animal nutrition under the term *locust meal*. In pig and poultry feeding, they can be offered either in live form or after processing. Common processing methods include boiling, drying, and subsequently grinding them into meal, which improves handling, storage, and incorporation into diets (Khusro et al., 2012). Locust meal is recognized as a rich source of crude protein (52–76%) and also supplies appreciable amounts of minerals, particularly iron (8.3–13.7 mg/100 g DM) and zinc (14.6–18.6 mg/100 g DM) (Khusro et al., 2012).

7. Crickets (*Gryllustestaceus walker*)

Crickets are commonly found in habitats such as paddy fields and fallow lands. They are highly adaptable and can thrive on diverse organic substrates, including forage-based diets, agricultural by-products, residues from the feed industry (such as spent grains and mung bean sprout waste), as well as various weeds. These low-cost and sustainable feed sources make cricket farming economically viable. Crickets are also relatively easy to rear under farm conditions, which explains their popularity in countries like Thailand, where approximately 20,000 farmers are engaged in cricket production (FAO, 2013). In terms of nutrition, crickets stand out for having a high crude protein content, often between 55% and 73%. Crickets are good source of Zn (515–1032 mg/kg) and Fe (31–100 mg/kg) which makes it's as a good alternative for protein and minerals in the diet of pigs (Makkar et al., 2014; Lu et al., 2022).

8. Silkworm

Different silkworm species reported in literature include ***Bombyx mori Linnaeus, Antheraea assamensis, Antheraea mylitta, Antheraea paphia*** and ***Samia cynthiaricini*** (Makkar et al., 2014). Silkworm pupae are obtained in bulk as waste material after silk is extracted from the cocoons by spinning or reeling processes (Khatun et al., 2005). The larval stage of the moth ***Bombyx mori*** is commonly known as the silkworm and is the primary source of global silk production, contributing nearly 90% of the commercial supply from its cocoons. Approximately 90% of commercial silk is derived from the cocoons of this domesticated insect (Ijaiya and Eko, 2009). The female moth lays a tiny, black egg from which the caterpillar grows. It grows to a full size of 7.5–10 cm in 4–6 weeks by continuously feeding on mulberry and shear butter leaves (Ijaiya and Eko, 2009). Silkworm is regarded as a very good unconventional source of protein (51.8-55.6%) for pig diets following adequate processing. It is also a strong source of iron (15.9 mg/100 g DM) and zinc (16.8 mg/100 g DM), which is an added benefit (Ijaiya and Eko, 2009).

Table 1. Mean levels of protein, iron, and zinc in different insect species evaluated as pig feed sources (FAO, 2013)

Common name	Scientific name	Crude protein (% DM)	Fe (mg/100 g DM)	Zn (mg/100 g DM)
House cricket	*Acheta domesticus*	62.9	9.1	19.9
Tropical house cricket	*Gryllodessigillatus*	70.0	4.23	13.9
Migratory locust	*Locusta migratoria*	59	13.7	14.8
Desert locust	*Schistocerca gregaria*	76	8.38	18.6
Lesser mealworm	*Alphitobiusdiaperinus*	67.85	21.80	26.80
Yellow mealworm	*Tenebrio molitor*	51.7	5.3	11.8
Silkworm	*Bombyx mori*	51.8	15.9	16.8
Termite	*Macrotermessubhyalinus*	38.8	61.9	9.5
Longhorn grasshopper	*Ruspoliadifferens*	43.7	14.8	14.9
Cornfield grasshopper	*Sphenarium purpurascens*	65.2	18	42

Iron and Zinc Bioavailability from Insect-Based Foods

The percentage of a nutrient that is absorbed from the diet and made accessible for usage by the body is known as nutritional bioavailability. It is influenced by factors like age, sex, nutritional status, and feed quality. The process of bioavailability includes the nutrient's release from food, digestion by enzymes, absorption in the intestines, transfer to the bloodstream or lymphatic system, distribution, and excretion. In vertebrates, iron (Fe) is mainly found as myoglobin and hemoglobin, while in insects, it primarily exists in cytochromes. The absorption efficiency of iron bound to cytochromes is considered comparable to that found in hemoglobin and myoglobin. Insects also store Fe as ferritin and holoferritin, which can hold thousands of Fe atoms, enhancing its bioavailability (FAO, 2013). Phytoferritin in legumes like soy is more bioavailable than Fe from reduced salts, as it protects Fe from anti-nutritional factors like phytates, oxalates, and tannins (Finke, 2002).

Processing of insects into insect meal

Using insect meal to feed pigs can be a sustainable and nutritious choice. Ensuring food safety in insect-based feed requires adherence to hygiene and safety standards comparable to those used for conventional food and feed ingredients.The processing method applied depends on the type of insect, associated safety concerns, and the intended end product. The processing pathway for producing insect meal is illustrated in Figure 1.

1. **Selection of Insects**

Black soldier fly larvae, grasshoppers, mealworms, locusts, crickets, silkworms and earthworms are among the often-employed insects.

2. **Insect Farming**

Establish an optimal environment for insect breeding, which includes appropriate containers, temperature, humidity, and ventilation. Offer organic waste or specialized feed that is suitable for the selected insect species (e.g., fruit scraps for black soldier fly larvae). Insects can effectively convert materials such as vegetables, fruits, grains, and animal waste into proteins and lipids.

3. **Harvesting**

Once the insects attain the required size or age, they are harvested either manually or using automated systems. Sieving is typically used to separate larvae, such as mealworms and smaller mealworms, from their substrate. Crickets and grasshoppers, on the other hand, can be collected manually or by gently shaking them out of their hiding spots inside the rearing system. By depriving the insects of food, some farms also implement a temporary fasting period prior to harvest (Garofalo et al., 2019). This practice encourages the insects to clear their intestine (Finke, 2002), which breeders believe enhances flavor and produces cleaner products with lower microbial levels.

4. **Processing**

   i. **Euthanization:** After harvesting, insects undergo several post-harvest treatments before consumption, the first step is to euthanize them. Typical methods for this process include freezing, immersing in hot or boiling water, and steaming. This step is crucial because it influences the final product's microbial load, nutrient content, color, and flavor, among other critical quality attributes (Larouche et al., 2019). The following euthanasia techniques have been investigated for black soldier fly larvae: blanching, desiccation, freezing, high hydrostatic pressure, grinding, and asphyxiation using vacuum, 100% CO_2, or 100% N_2 (Larouche et al., 2019). In terms of processing time, final moisture content, lipid oxidation, microbiological load, and color stability, blanching—immersion in boiling water for 40 seconds—was the most successful method among them. In order to inactivate vegetative microorganisms without damaging bacterial spores, blanching entails short boiling the food and then quickly chilling it in cold water (Xiao et al., 2014).

   ii. **Cleaning:** The euthanasia procedure can be combined with washing or rinsing, as is done with fresh produce, to lessen germ contamination. Research has shown that rinsing smaller mealworms with sterile distilled water that contains antimicrobial agents such as sodium hypochlorite, hydrogen peroxide, or ethanol enhances results (Crippen and Sheffield, 2006).

   iii. **Milling:** To obtain a uniform product such as powder or paste, edible insects are often subjected to milling or grinding. This process can be applied to fresh insects, after blanching for wet milling, or once the insects have been dried for dry milling. Because wet milling creates a liquid-like material that is simpler to process, it is frequently preferred in industrial applications (Dossey, 2015). However, the high moisture content in this method can lead to microbial instability in the resulting product.

iv. **Drying:** Wet milling can be followed by drying to create a powder, which will increase shelf life and yield a stable product (Dossey et al., 2016). Several drying techniques are available for insects, including oven drying, dehydration, freeze drying, microwave drying, and sun drying, while spray drying is commonly used for drying insect paste. This method involves introducing the paste into hot air, allowing each droplet to dry individually, resulting in a quick process that yields uniform products with improved nutritional quality (Dossey et al., 2016). However, due to the limitations of spray drying with high-fat products, drum drying is frequently utilized instead (Dossey et al., 2016).

Type of Mill

The final properties of the powder or paste can be greatly impacted by the type of blender used to produce insect food. For example, one study reported that defatted mealworm meal processed with a jet mill had lower moisture content, higher brightness, more uniform particle size, and greater consumer acceptance compared to powders produced using pin, hammer, or cutter mills (Son et al., 2019).

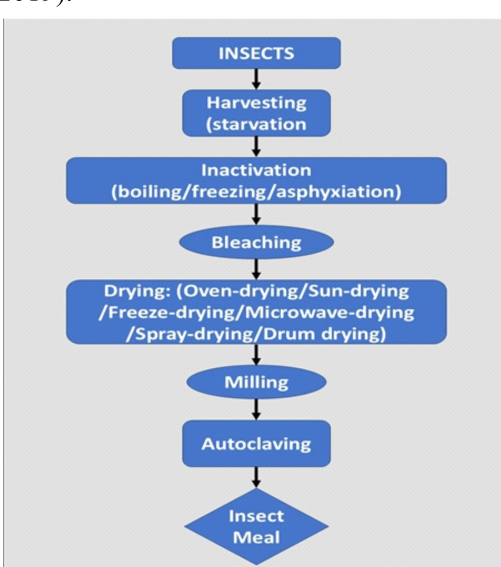

Figure 1. Processing pathway for the production of insect meal (Dossey et al., 2016)

Exploring Insect-Based Products in Swine Research

1. Effect of feeding insect meal on growth performance and nutrient digestibility

Because of its nutritional and functional qualities, Tenebrio molitor (TM) larvae meal has been studied as a possible protein source for pig diets. Jin et al. [19] found that weaned pigs' body weight (BW) and average daily gain (ADG) improved linearly when TM meal was added to their diets at a rate of 0–6% during a five-week period. The gain-to-feed ratio (G:F) and average daily feed intake (ADFI) both showed numerical increases.The study also indicated improved protein and nitrogen utilization, as shown by increased crude protein digestibility, nitrogen retention, and decreased blood urea nitrogen levels.The digestibility of dry matter (DM), gross energy (GE), and nitrogen, as well as growth performance, were not significantly affected by replacing 20% of fishmeal with Tenebrio molitor larvae (Ao et al., 2020). Ji et al. (2016) found that substituting 5% plasma protein with 5% TM larvae powder had no impact on the growth of pigs weaned at 14 days over an eight-week period. Additionally, growing pigs fed diets containing TM larvae had higher standard ileal digestibility (SID) of gross energy, arginine, and cystine than those fed diets containing fish meal (Yoo et al., 2019). Pigs given Tenebrio molitor larvae had better standardized ileal digestibility (SID) of gross energy, arginine, and cystine than pigs fed fish meal diets (Yoo et al., 2019).

In comparison to diets made with meat, chicken, or fish meal, diets containing TM larvae also tended to improve the SID of dry matter, crude protein, and amino acids (sustainable protein source for weanling pigs (Larouche et al., 2019; Yoo et al., 2019). In a similar vein, Chia et al. (2019) assessed the substitution of black soldier fly larval meal (BSFLM) for fish meal (FM) in the meals of 40 hybrid developing pigs. The animals were divided into five groups: one control (0% BSFLM, 100% FM) and four treatment groups where FM was replaced at 25%, 50%, 75%, and 100%. Their results indicated that BSFLM can successfully replace FM in developing pig diets because there were no discernible differences in average daily feed intake (ADFI), average daily gain (ADG), body weight gain (BWG), or feed conversion ratio (FCR). In finishing pigs, however, Chia et al. (2021) observed that increase in the inclusion of BSFLM (9–14%), replacing 50–100% of FM, improved final body weight, ADG, feed conversion ratio, and carcass weight. At different dietary proportions across three feeding phases, with or without amino acid supplementation, it was also determined that feeding dried black soldier fly prepupae meal to early-weaned pigs as a substitute (0, 50, or 100%) for dried plasma meal was a workable approach. However, full replacement of dried plasma did not perform as well as the control, suggesting potential refinements like cuticle removal may be needed for better suitability (Newton et al., 2005). Yu et al. (2019) investigated how the growth performance of finisher pigs was affected by feeding *Hermetiaillucens* larvae at 0, 4, and 8% (HI0, HI4, and HI8 groups, respectively). According to the findings, pigs given the HI4 diet had a lower ($P < 0.05$) feed-to-gain ratio and a significantly greater ($P < 0.05$) final body weight and average daily gain than the HI0 and HI8 groups.

2. Effect of insect meal on blood biochemical parameters

Hematological indicators including red and white blood cell counts were not significantly affected when growing pigs were fed black soldier fly larvae meal (BSFLM) at different amounts (0–100%) in place of fish meal Chia et al. (2019). However, pigs receiving diets where fish meal was substituted at 75% and 100% exhibited elevated neutrophil levels.Platelet counts were lower in pigs fed 25%, 75%, and 100% diets than in those fed 0% and 50%. Furthermore, blood cholesterol levels were unaffected by the addition of BSFLM to the diet. As the inclusion level rose throughout phase II (14–35 days), Jin et al. (2016) found that introducing dried mealworm (*Tenebrio molitor*) at 0%, 1.5%, 3.0%, 4.5%, and 6.0% decreased blood urea nitrogen and enhanced insulin-like growth factor. Another study found that replacing fish meal with dried mealworm at 50% and 100% in weanling pig diets had no effect on blood parameters, including total RBCs, WBCs, lymphocytes, and monocytes, throughout the trial (Jin et al., 2016). Overall, these studies indicate that insect meals do not adversely affect pig health and can be incorporated into their diets.

1. Effect of insect-based proteins on immune responses in pigs

According to Ko et al. (2020), substituting fish meal with dried mealworm at 50% and 100% in weanling pig diets significantly increased immunoglobulin G (IgG) levels during phase I (0–14 days). They also noted a numerical decrease in pro-inflammatory cytokine IL-6 at the 50% replacement level, with no effects on IL-1β or TNF-α production during phases I and II (15-28 days). Yu et al. (2019) observed that incorporating *Hermetiaillucens* larvae at 4% and 8% in the diets of finishing pigs led to a significant ($P < 0.05$) reduction in TLR-4 expression and the pro-inflammatory cytokine IFN-γ. Additionally, the anti-inflammatory cytokine IL-10 rose at the 4% inclusion level, and genes linked to the intestinal barrier, such as ZO-1, occludin, and mucin-1, showed increased expression. 6% mealworm supplementation did not significantly alter blood IgG concentrations in young piglets (Jin et al., 2016). Overall, these studies suggest that insect meal does not negatively affect immune cells and may have immunomodulatory effects in pigs.

2. Effect of insect meal on gut health

Yu et al. (2019) found that supplementing finishing pigs' diets with *Hermetiaillucens* larvae at 4% and 8% levels improved gut health. Beneficial bacterial communities, such as *Lactobacillus, Pseudobutyrivibrio, Roseburia*, and *Faecalibacterium*, significantly increased ($P < 0.05$) at the 4% inclusion level, while Streptococcus decreased. Furthermore, toxic protein fermentation products such total amines, cadaverine, tryptamine, phenol, p-cresol, and skatole dramatically decreased ($P < 0.05$), but colonic metabolites such as total short-chain fatty acids, butyrate, and isobutyrate rose significantly (Yu et al, 2019; Ramos-Elorduy et al., 2002). Supplementing with insect meal does not adversely affect intestinal integrity or nutrient absorption, according to another research (Ko et al., 2020). Ji et al. (2016) noted that replacing 5% plasma protein with 5% mealworm powder reduced diarrhoea incidences during weeks 2 to 4. Furthermore, the liver and gastrocnemius muscle of pigs fed insect diets showed no indications of oxidative stress or the activation of stress-sensitive signalling pathways, according to Ringseis et al. (2021).

Challenges in Incorporating Insects as Feed Ingredients

Insects hold considerable potential as feed ingredients for swine diets because of their nutrient profile, digestibility, and functional properties. To properly use them in swine nutrition, a number of issues must be resolved.

First, standardized protocols for insect production—including rearing, processing, and storage—are crucial to ensure a consistent large-scale supply.Establishing these standards will help manage critical food safety hazards for both consumers and livestock. Moreover, adopting novel processing techniques can also improve the quality and utility of insect-based products. As demand for insects rises and production technology improves, reliable mass production for feed applications is expected to become achievable.

Second, the current market price of insects is higher than conventional protein sources like soybean meal (SBM) and fish meal, limiting their competitiveness. Insect producers are generally smaller operations, primarily serving markets for birds and reptiles. To make insects a viable option for swine feed, large-scale production systems need to be implemented to stabilize supply and increase production efficiency, which could lead to lower prices.

Lastly, more study is required to completely comprehend the functional and nutritional advantages of pigs eating insect-based products. Finding the ideal inclusion amounts of insect products for various growth periods while accounting for growth, reproduction, pork quality, and general health is crucial, even though the majority of research has concentrated on growth performance and nutrient digestibility. In addition, the potential functional effects of insect components, such as chitin and other bioactive compounds, warrant thorough investigation.Safety concerns, including the presence of toxic substances, antibiotic resistance, and contamination from pathogens or heavy metals, also need to be thoroughly addressed.

CONCLUSION

Insects represent a promising and sustainable alternative for pig nutrition, offering both high-quality protein and valuable trace minerals such as iron and zinc. Their use not only addresses nutritional challenges but also supports circular economy practices by utilizing organic side streams. However, issues such as nutrient variability, processing methods, and regulatory acceptance remain to be resolved. With continued research and innovation, insects could become an integral part of sustainable pig production in the future.

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