

REVIEW OPEN ACCESS

Ruminants

Are Insects a Feasible Option or Just a Hyped Promise in Ruminant Nutrition? A Systematic Review of What Has Been Done and What Lies Ahead

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ABSTRACT

Insects have emerged as a promising sustainable feed alternative for ruminants, offering high nutrient density and potential environmental benefits in the context of growing pressures on conventional protein sources. This systematic review critically evaluates the state-of-the-art literature written in English and published in peer-reviewed journals from 2015 to 2025 on the use of insect-based feeds in ruminant nutrition, synthesising evidence from in vitro and in vivo studies, discussing their outcomes and elucidating underlying mechanisms to guide future research. Most insect species studied include black soldier fly (*Hermetia illucens*) larvae, housefly (*Musca domestica*) larvae, adult crickets (*Gryllus bimaculatus*), silkworm (*Bombyx mori*) pupae, and mealworm (*Tenebrio molitor*) larvae, with studies highlighting their favourable chemical composition, particularly high protein content and rich fatty acid profiles. In vitro and in vivo research, though occasionally inconsistent, shows promising effects on rumen fermentation, methane production, growth performance, product quality, and animal health. Nevertheless, inconsistent results, driven by variations in insect species, processing methods, and inclusion levels, highlight significant knowledge gaps. Challenges include non-standardised nutrient profiling, limited long-term health and performance studies, regulatory disparities, high production costs, scalability constraints, and underexplored consumer acceptance of sensory and market aspects. While insects offer opportunities for waste bioconversion and reduced ecological footprints, their integration requires targeted research into optimised feed formulations, longitudinal health studies, and robust regulatory frameworks. This review emphasises the necessity of multidisciplinary research to clarify the nutritional, environmental, and economic viability of insect-based feeds, paving the way for sustainable ruminant production systems.

1 | Introduction

In recent years, the ruminant sector, a fundamental pillar of global food security, has faced unprecedented challenges driven

by climate change, the COVID-19 pandemic, and geopolitical conflicts like the Russia–Ukraine crisis (Urak et al. 2024). In this global scenario, feed supply is a key factor that directly affects ruminant health, product quality, and profitability. It

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has experienced multifaceted disruptions through supply chain interruptions, price volatility and market uncertainties. Simultaneously, these issues exacerbate long-standing sustainability challenges within the agri-food sector (Pexas et al. 2023; Urak et al. 2024). Historically, the intensification of ruminant production systems mainly relied on soybean meal (SBM) and fish meal (FM) as primary protein sources (Pexas et al. 2023). This dependency exacerbates price volatility, food-feed competition, land use issues, logistical challenges, and greenhouse gas (GHG) emissions, amplifying eco-environmental concerns (Pexas et al. 2023). These factors, coupled with evolving animal welfare considerations and consumer demand for healthier ruminant products, dictate an urgent search for circular, sustainable and eco-friendly protein and energy sources for feeding ruminants to support ongoing attempts to achieve the Sustainable Development Goals (SDGs), specifically aimed at eliminating hunger by 2030 (FAO 2022).

Insects offer a promising solution to challenges associated with conventional protein and energy sources due to their rich nutritional profile, providing essential amino acids, fats, vitamins, and minerals, positioning them as a well-balanced feed option for animals (Fu et al. 2025). By converting a wide range of organic waste (such as food scraps, agro-industrial byproducts, and manure) into high-quality protein and fat, insects provide a sustainable solution to both waste management issues and the growing demand for animal feed (Smetana et al. 2023). Compared to conventional protein sources, insects require significantly less land, water, and feed to produce equivalent protein yields (Smetana et al. 2023; Fu et al. 2025).

Insects are increasingly used as a feed ingredient across various livestock species, including broiler chickens (Malematja et al. 2024), laying hens (Montalbán et al. 2024), turkeys (Hajhamidiasl et al. 2025), ducks (Gariglio et al. 2019), quail (Liu et al. 2025), swine (Von Jeinsen and Weinrich 2023), and aquatic species (Roccatello et al. 2024). However, their inclusion in ruminant diets remains limited due to concerns about potential *Bovine Spongiform Encephalopathy* (BSE), mad cow disease, transmission, despite a lack of supporting evidence (Gao et al. 2024).

Above all, in the context of global warming, mounting population, resource depletion, and conflicts, insects are a viable option for meeting the booming demand for ruminant feed in a circular, sustainable, and eco-friendly manner, advancing SDGs and supporting long-term global food security (Hancz et al. 2024; Gonzalez-Ronquillo et al. 2025). However, despite their numerous benefits, challenges are still faced in incorporating insects into ruminant rations. A primary obstacle is the absence of regulatory frameworks, as approval for using insects in ruminant diets has not yet been granted in many countries, limiting widespread adoption (Renna et al. 2023; Gasco et al. 2023; Gao et al. 2024). Consumer acceptance and market trends are also under investigation and could shape the application of insects as ruminant feed. Furthermore, insect rearing and processing methods require further optimisation to enhance efficiency and scalability (Gao et al. 2024). This systematic review aims to synthesise the current body of scientific evidence on the use of insect-based feeds in ruminant nutrition, encompassing both in vivo and in vitro studies. It also highlights existing knowledge gaps, explores safety and regulatory considerations, assesses economic viability, and

outlines future research directions necessary to scale up this emerging solution for sustainable ruminant production systems.

2 | Materials and Methods

A systematic literature search was conducted to identify all relevant studies evaluating the application of insects in ruminant diets. The search followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Page et al., 2021) and covered studies published between 2015 and July 2025. The following electronic databases were systematically searched: PubMed / MEDLINE, Scopus, Web of Science, ScienceDirect and Google Scholar.

Search terms were developed using Boolean operators and grouped into three thematic blocks: (1) Population: ('Ruminant' OR 'Cattle' OR 'Dairy cow' OR 'Sheep' OR 'Goat' OR 'Lamb' OR 'Kid' OR 'Heifer' OR 'Small ruminant'); (2) Intervention: ('Insects' OR 'insect-based feeding' OR 'Mealworm' OR 'Black Soldier Fly' OR 'Cricket' OR 'Grasshopper' OR 'Housefly'); (3) Outcomes: ('Performance' OR 'Feed intake' OR 'Milk yield' OR 'Rumen fermentation' OR 'Digestibility' OR 'In vitro gas production' OR 'Methane emission').

Studies were included if they were peer-reviewed, full-length research articles or meta-analyses published in English and focused on ruminants, and if they evaluated the use of insect-based feeds on some in vitro and/or in vivo parameters. In addition, exclusion criteria were studies on non-ruminant species, conference abstracts without full data, qualitative reports, or non-English publications.

Using the search strategy described above, an initial set of 266 articles was retrieved from the selected databases. Duplicate records were removed, and a reviewer assessed titles and abstracts against the inclusion criteria. A total of 177 full-text articles were retrieved and evaluated for eligibility. Following a detailed review, 36 studies met all the inclusion criteria and were included in the final synthesis, as illustrated in the PRISMA flow diagram (Figure 1).

3 | A Glance at Insects in Ruminant Nutrition

The use of insects as food has a long anthropological and ecological history, with numerous human cultures consuming various insect species either intentionally or incidentally (Meyer-Rochow et al. 2022). Historical records indicate that even ancient civilisations, such as the Greeks and Romans, appreciated certain edible insects (Meyer-Rochow 1975). However, the concept of using insects systematically as a feed source for domestic or pet animals, particularly in controlled settings, is relatively recent. The turning point in this narrative came when global organisations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) highlighted insects not only as human food but also as a strategic feed ingredient for livestock to alleviate feed insecurity (van Huis et al. 2013). Since then, considerable attention has been devoted to the nutritional, environmental, and circularity-related benefits of incorporating insect-based products in animal nutrition systems. While early studies focused on

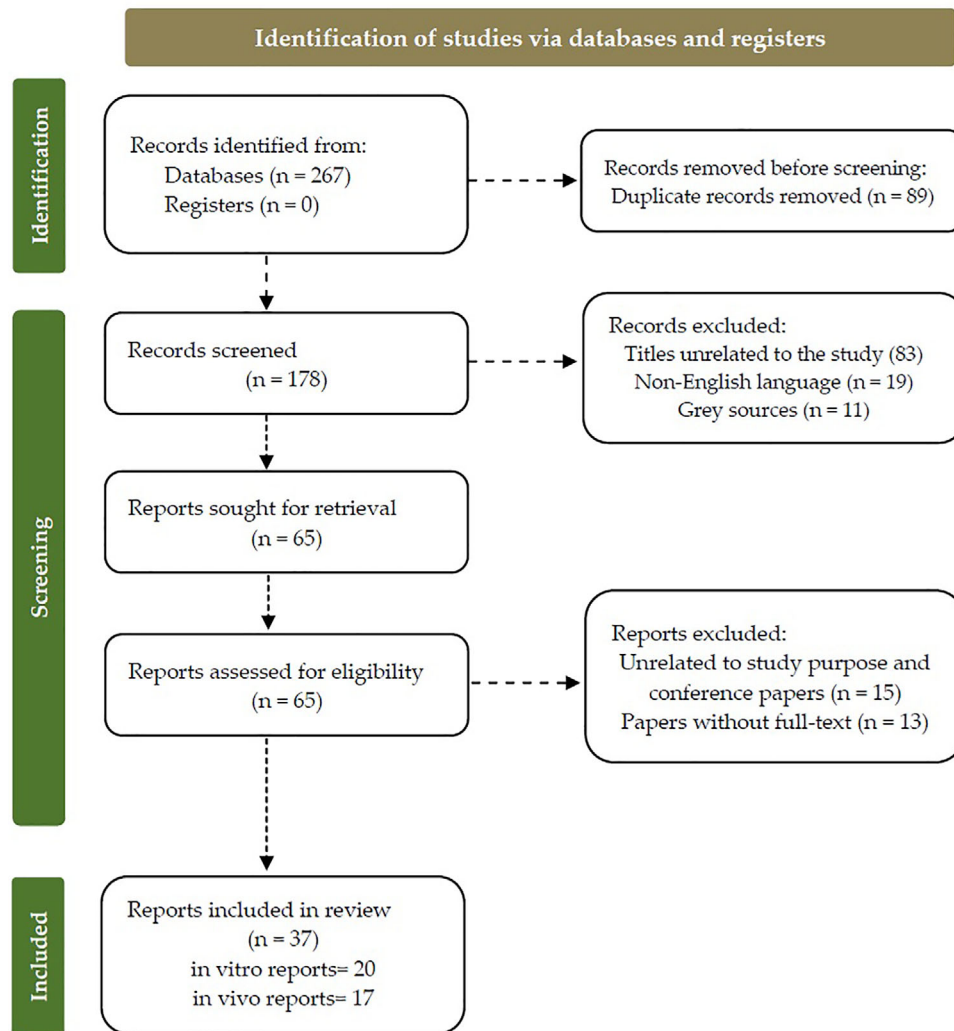


FIGURE 1 | Schematic diagram of the systematic review process.

using insects in monogastric animal diets, interest in applying insects to ruminant feeding systems has gradually increased. The following sub-sections provide an overview of the main insect species studied, their processing methods, nutritional value, and anti-nutritional compounds relevant to ruminant systems.

3.1 | Insect Species Studied

Although insect use in ruminant nutrition is still in its infancy, several species have been evaluated for their potential as alternative protein or fat sources. Although a greater number of species have been studied in ruminants, the most significant and widely used species are described below (Figure 2).

3.1.1 | Black Soldier Fly (*Hermetia illucens*, HI)

HI is classified as a *Diptera* in the *Stratiomyidae* family and is native to the Americas but now distributed globally in tropical and temperate regions, with an optimum temperature range of 25°C to 30°C (Čičková et al. 2015). Adult flies, resembling wasps, are black and measure 15–20 mm in length. Larvae, reaching

approximately 27 mm long and 6 mm wide, weigh up to 220 mg at their final stage, appearing dull white and maturing within two months (Cai et al. 2022). Only water is consumed by adult flies, which are harmless to humans. Organic waste, including manure, kitchen scraps and rice straw, is consumed by black soldier fly larvae (BSFL) (Raman et al. 2022). Mating occurs at lekking sites, where males encounter females. Eggs are laid by mated females in prepared organic waste within 2 days, after which they die (Tomberlin and Sheppard 2002). In live, chopped, or dried and ground forms, BSFL are frequently used as feed for ruminants in Asian countries (Astuti and Wiryawan 2022).

3.1.2 | Mealworms (*Tenebrio molitor*, TM)

TM, belonging to the *Tenebrionidae* family, is recognised as the larval stage of the common grain beetle, also known as the yellow worm. Globally distributed in terrestrial regions, their larvae are extensively utilised as protein-rich animal feed due to their high protein and lipid contents. A life cycle ranging from 280 to 630 days is exhibited by mealworms, with larvae hatching after 10–12 days at 18–20°C and maturing within 3–4 months, potentially extending to 18 months. Mature larvae, light yellow-

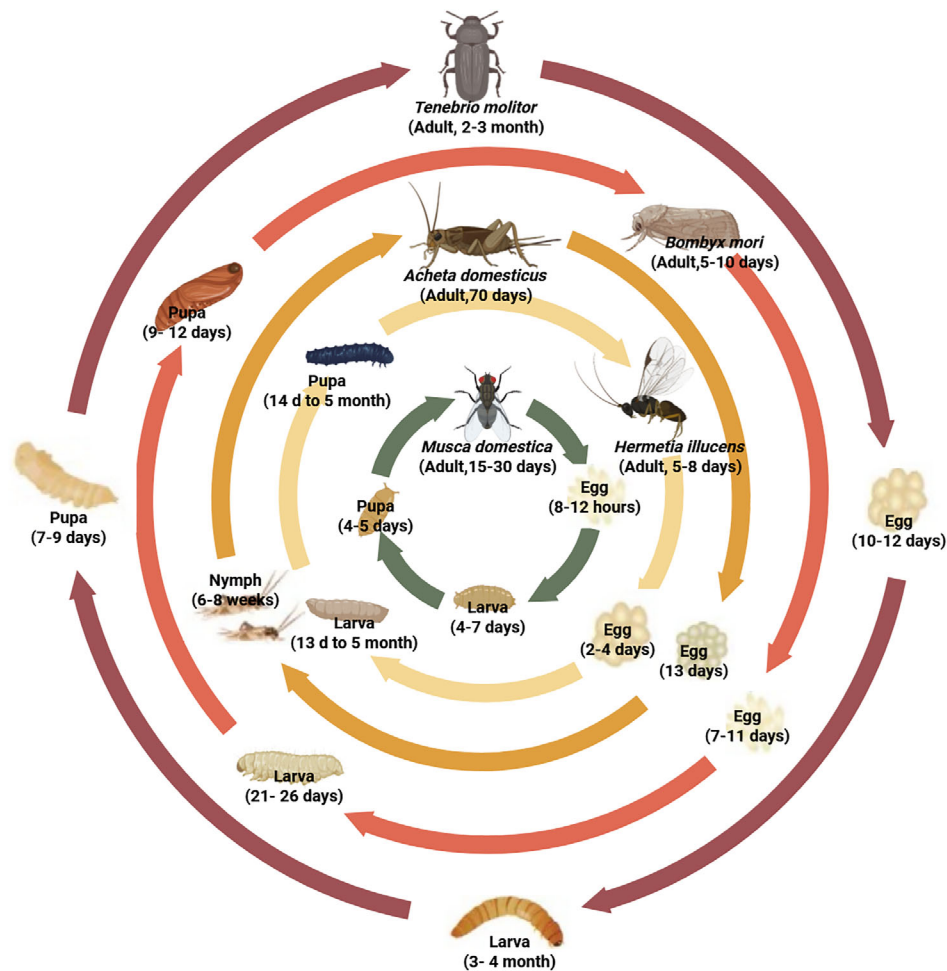


FIGURE 2 | The life cycles of commonly studied insects in ruminants (created with BioRender). The common house fly (*Musca domestica*) is at the centre, followed by the black soldier fly (*Hermetia illucens*), the house cricket (*Acheta domestica*), the silkworm (*Bombyx mori*) and the yellow mealworm (*Tenebrio molitor*).

brown, measure 20–32 mm in length and weigh 130–160 mg. Primarily, mealworms are employed in the production of feed for pets, zoo animals, and occasionally livestock.

3.1.3 | Crickets (*Gryllinae* sp., GS)

GS are classified under the order *Orthoptera* and family *Gryllidae*, encompassing over 6000 described species that are widely consumed in Africa, South America, and Asia (van Huis et al. 2013). GS are normally 15–25 millimetres in size, depending on the species, and can be black, red, or brown (Alexander 1968). As non-wood wild products, crickets are found globally in natural habitats, except in cooler regions beyond 55° latitude, with the highest species diversity observed in warm tropical areas conducive to rapid development (Masaki 2013). Organic materials are consumed by crickets, which thrive at 28–30°C, allowing approximately 2000 individuals to be reared per square metre. Collection from the wild is typically conducted at night using artificial lighting or in the early morning when low temperatures render crickets dormant (Clifford and Woodring 1990). A short life cycle of 60–70 days is exhibited by GS, with females producing 200–1500 eggs over three weeks (Sengendo et al. 2025). Eggs are laid in moist substrates; nymphs are hatched from eggs after 15–

25 days, resembling adults but distinguished by their smaller size and absence of wings. Development into adults is completed by nymphs in approximately 10 weeks, influenced by temperature. Up to three generations may be produced annually in southern regions (Sengendo et al. 2025).

3.1.4 | Housefly (*Musca domestica*, MD)

MD, classified under the order *Diptera* and family *Muscidae*, is distributed worldwide and sustained by manure and organic waste (Abbas et al. 2013). Optimal production is achieved at warm temperatures (>25°C) with adequate moisture. Larvae emerge from eggs within 8–12 h, with the larval stage lasting approximately 5 days and the pupal stage extending 4–5 days. Up to 500–600 eggs, or more, can be laid by adult females under managed conditions (Sankara et al. 2023).

3.1.5 | Silkworm (*Bombyx mori*, BM)

BM was domesticated approximately 5000 years ago. The pupae are consumed in silk-producing regions like China, India and

Thailand, containing about 60% crude protein and 25% fat on a dry matter (DM) basis (Sharma et al. 2022). The silkworm moth undergoes four life stages—egg, larva, pupa, and adult—lasting approximately 7–11, 21–26, 9–12 and 5–10 days, respectively (Nurkomar et al. 2022). Females begin oviposition 5.5–8.5 h after emergence, laying about 350 eggs in their lifetime. Industrial rearing is established under controlled environmental conditions for silkworm growth, with 24–27°C and 70–90% relative humidity. Silkworms are typically fed mulberry leaves, with growth and development influenced by diet quality (Sharma et al. 2022). Optimal growth and fecundity are ensured by providing sufficient space and low rearing densities, while the preference for an expensive mulberry leaf diet limits large-scale rearing for ruminant feed (van Huis et al. 2013).

3.2 | Rearing Substrate, Processing Methods and Forms

The nutrient composition of insects is profoundly shaped by the rearing substrate (Schneider et al. 2025; Bellezza Oddon et al. 2025). Insects reared on nutrient-rich organic substrates (e.g., cereal by-products, brewery waste or agro-industrial residues) typically exhibit higher crude protein, essential amino acid and mineral contents, whereas those raised on manure- or lignocellulosic-based substrates may show elevated fibre and ash levels but lower digestibility and lipid quality (Hopkins et al. 2021). Studies have shown that modifying the rearing diet, for instance, by enriching the substrate with oilseeds or food waste, can markedly alter the fatty acid profile, increasing α -linolenic acid (C18:3 n-3) and linolenic acid (C18:2 n-6) proportions in HI and TM larvae (Riekkinen et al. 2022). BM pupae, exclusively reared on mulberry leaves, display a consistent fatty acid profile rich in C18:3 n-3, whereas GS-fed varying cereal-based diets show wide fluctuations in n-6:n-3 ratios (Sánchez-Muros et al. 2014). Likewise, higher carbohydrate or protein levels in the rearing medium affect growth performance, chitin deposition, and the overall amino acid balance (Schneider et al. 2025; Riekkinen et al. 2022). Therefore, variability in insect nutrient composition among studies often reflects differences in rearing conditions rather than species effects alone. In addition, post-harvest treatments, including blanching, drying temperature, and defatting, further influence nutrient retention and stability, particularly for heat-sensitive amino acids and polyunsaturated fatty acids (Bellezza Oddon et al. 2025).

For insect meal production, insects are typically processed into homogenous forms like powders or pastes, using either wet or dry milling. Wet milling, commonly applied at an industrial level, allows easier handling but yields a microbially unstable product that requires refrigeration ($\leq 5^\circ\text{C}$) and rapid use (Parniakov et al. 2022). In contrast, dry milling produces shelf-stable powders suitable for ambient storage and commercial distribution (Ojha et al. 2021). Spray drying is the preferred method for drying insect pastes, offering rapid and uniform dehydration with minimal nutritional loss (Hernández-Álvarez et al. 2021). However, its limitation with high-fat materials necessitates alternatives like drum drying, which may result in uneven dehydration and lower product quality (Hernández-Álvarez et al. 2021).

Insect meals are categorised into full-fat (containing 40–70% crude protein [CP] and 20–70% ether extract [EE], DM basis) and defatted forms ($\approx 55\%$ CP and less than 12% EE, DM basis) based on previous studies (Figure 3). Defatting can occur before or after milling, using mechanical, physical, or chemical methods, each influencing shelf life, nutrient profile, and sensory attributes (Ojha et al. 2021; Bellezza Oddon et al. 2025). Mechanical defatting before milling may limit enzymatic hydrolysis triggered by lipases and proteases, which occurs during cell disruption (Sindermann et al. 2021). Additional hydrolysis can be promoted using commercial enzymes and water, followed by drying (Sindermann et al. 2021). Solvent extraction, though yielding higher fat removal, poses environmental and sensory drawbacks, for example, reduced flavour and acceptability in n-hexane-treated mealworm products compared to pressure-defatted counterparts (Liceaga 2021).

Thermal processing is a critical control point for microbial safety and can be applied pre- or post-milling (Kamau et al. 2020). Decontaminating after milling is often preferred, as it targets the elevated microbial load released from the gut microbiota. However, high temperatures may cause undesirable changes such as browning or burnt flavours (Ojha et al. 2021). Blanching, used to reduce microbial load and enzyme activity, may cause nutrient leaching and increase drying energy needs but can effectively reduce *Enterobacteriaceae* counts. Still, bacterial spores may survive, necessitating further treatments (Kamau et al. 2020).

Fermentation offers a promising stabilisation approach. It enhances safety, functional properties, and bioactive compounds content. For instance, fermentation with *Yarrowia lipolytica* or *Debaryomyces hansenii* improved nutritional profiles and antimicrobial properties (Patrignani et al. 2020). Acidification using starter cultures such as *Pediococcus acidilactici* can suppress spoilage organisms within days (Borremans et al. 2018), though lipid oxidation during storage may occur. Additives like sodium nitrite and sodium lactate can also reduce sulphite-reducing bacteria, preventing unpleasant off-odours like hydrogen sulphide (Borremans et al. 2018).

3.3 | Nutritional Value and Anti-Nutritional Factors

The nutritional composition of insects greatly varies by species, developmental stage, and processing method (Gasco et al. 2023) (Figure 4). Overall, insects are rich in protein, offering a more balanced amino acid profile and higher levels of essential amino acids compared to plant-based feedstuffs (Gasco et al. 2023). Studies focused on ruminant species reported that the CP content of full-fat insect meals ranges from 30% to 70% (on a DM basis) with significant variations across species; for example, CP levels are established at 57.5–62.73% DM for *Bombyx mori* (Ahmed and Nishida 2023; Ahmed et al. 2025), 15.7–51.5% DM for *Hermetia illucens* (Odeon et al. 2025; Carrasco and Drewery 2024), 52.4–56.7% DM for *Tenebrio molitor* (Robles-Jimenez et al. 2025b), and 47.3–62.5% DM for *Gryllus bimaculatus* (Hervás et al. 2024; Ahmed and Nishida 2023). However, the full bioavailability of this protein may be limited due to chemical bonding with the exoskeleton, which is rich in chitin. The CP digestibility in ruminants, typically rated high at 77–98%, is often overstated

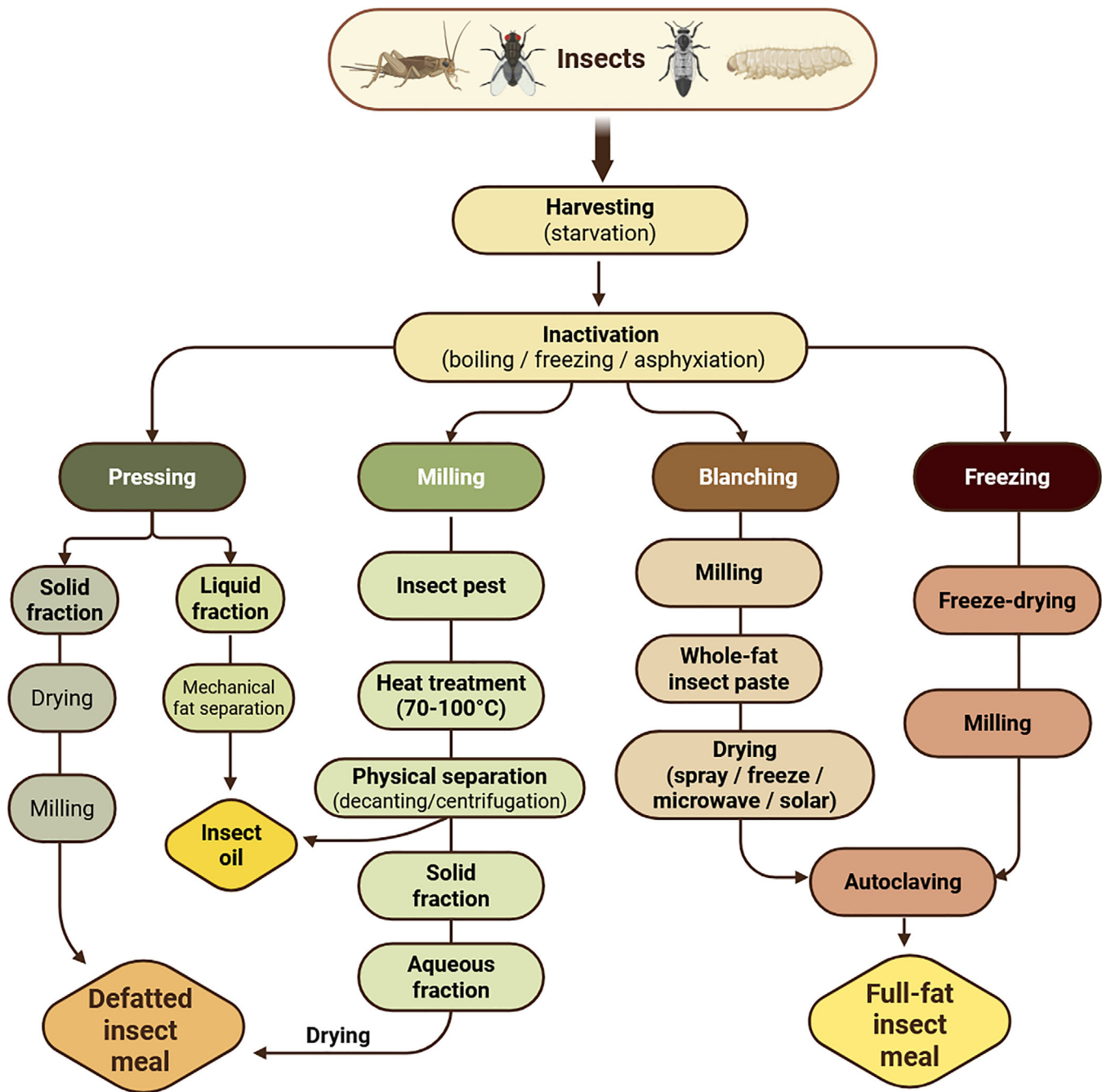


FIGURE 3 | Schematic overview of processing methods of insect meals, illustrating three major outputs of insect processing: full-fat meals, defatted meals and insect oil/fat (created in BioRender).

because of chitin presence (Boussalia, 2021). Insects are also rich in essential amino acids (lysine, methionine and threonine), their concentrations being comparable or superior to those found in SBM and FM (Sánchez-Muros et al. 2014; Gasco et al., 2020).

Fat content is significantly influenced by both species and processing methods, with full-fat meals typically containing 15–35% lipids, being mainly characterised by linoleic acid (C18:2 n-6) (with some exceptions, such as the high lauric acid [C12:0] and α -linolenic acid [C18:3 n-3] concentrations in HI and BM, respectively) (Gasco et al. 2023; Toral et al. 2025). Apart from

the very high concentrations of C12:0 in HI, in insects the most common saturated fatty acids (SFAs) are C18:0 and C16:0. Among the monounsaturated fatty acids (MUFAs), oleic acid (C18:1 n-7) is present in all studied species. Regarding polyunsaturated fatty acids (PUFAs), certain species such as *Tenebrio molitor*, *Bombyx mori*, and *Acheta domesticus* are known to contain high levels of C18:2 n-6 and varying amounts of C18:3 n-3, but they lack C20:3 n-6 and C20:4 n-6. In contrast, other species are higher in C20:3 n-6 and C20:4 n-6, with lower levels of C18:2 n-6 and C18:3 n-3. Notably, compared to soybean oil, insect meal exhibits lower levels of C18:2 n-6 (Sánchez-Muros et al., 2014; Sogari et al. 2019).

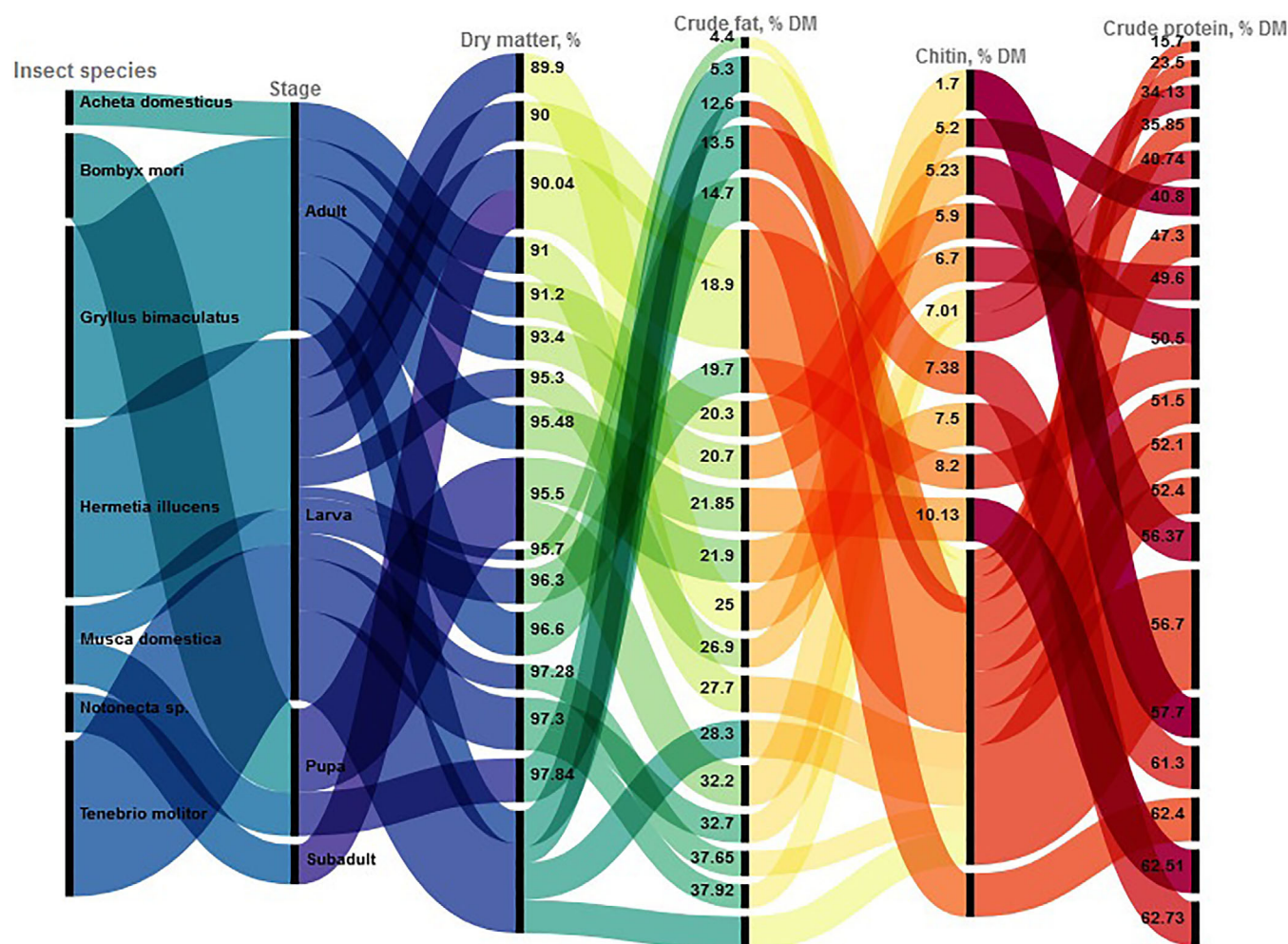


FIGURE 4 | Schematic diagram illustrating the chemical composition across the major developmental stages of the main insect species studied for ruminant nutrition. The values presented are based on data compiled from the literature, as detailed in Supplementary Table S1.

For incorporating insects into animal feed, proximate composition—including DM, CP, EE, NDF, ADF and ash—should be analysed, even if data are provided by producers (Gasco et al. 2023). When CP is measured using the Kjeldahl method, species- and product-specific nitrogen-to-protein conversion factors (Kp) must be applied instead of the conventional 6.25 to avoid 10–15% overestimation. For example, Kp values of 4.76 ± 0.09 for whole larvae (specifically, 4.75 for *T. molitor*, 4.86 for *A. diaperinus* and 4.67 for *H. illucens*) and 5.60 ± 0.39 for protein meals (specifically, 5.59 for *T. molitor*, 5.59 for *A. diaperinus*, and 5.62 for *H. illucens*) have been reported for three insect species, *Tenebrio molitor*, *Alphitobius diaperinus*, and *Hermetia illucens*, respectively (Janssen et al. 2017). Additionally, amino acid profiles, fatty acids, minerals, vitamins, and energy values should be assessed for balanced feed formulation (Bellezza Oddon et al. 2025).

Chitin ($C_8H_{13}O_5N$)_n, a major component of the insect exoskeleton, protects insect soft tissues, and its content, usually ranging from 5 to 10% of DM, varies depending on species and developmental stage (Gasco et al. 2023). Chitin is a linear polymer primarily composed of β -(1→4)-linked 2-acetamido-2-deoxy- β -D-glucopyranose units, with some β -(1→4)-linked 2-amino-2-deoxy- β -D-glucopyranose units, which render it insoluble in water

(Shah et al. 2022). Chitin is converted into chitosan through partial or complete deacetylation, either enzymatically (using chitin deacetylase) or under industrial alkaline conditions. Chitosan is a linear polysaccharide consisting of D-glucosamine and N-acetyl-D-glucosamine units linked by β -(1→4) bonds (Shah et al. 2022).

The role of chitin and chitosan in animal feed remains debated (Gasco et al. 2023). Some studies have linked reduced diet digestibility and intake in ruminants to chitin presence in insect-based feeds (Jayanegara et al., 2020). Conversely, chitin has also been reported to exhibit immunostimulatory, antimicrobial, and anti-inflammatory properties in monogastrics (Gasco et al. 2023).

Anti-nutritional factors other than chitin, including phenolic compounds, oxidised lipids, and biogenic amines, have also been identified in insect meals, particularly when reared on low-quality or contaminated substrates. Additionally, the accumulation of heavy metals and the risk of pathogen contamination remain concerns, highlighting the need for strict quality control and regulatory monitoring (van Huis et al., 2013).

Insects, beyond their nutritional value, contain bioactive compounds that could support animal health. Key groups include

antimicrobial peptides (AMPs), fatty acids (e.g., lauric acid, myristic, palmitic, oleic, linoleic acid and α -linolenic acid), and polysaccharides (e.g., chitin and chitosan) (Hancz et al. 2024). Insect proteins also offer antioxidant benefits, protecting against oxidative damage. A synergistic action among AMPs, fatty acids, and chitin or chitosan may provide a promising approach to counter antimicrobial resistance (Hancz et al. 2024).

4 | Synthesising the Evidence: What We Know So Far

While live insects and their derivatives have been identified as suitable protein and fat sources for monogastric diets, limited data have been reported regarding their inclusion in ruminant diets (Gao et al. 2024). This gap is largely due to regulatory bans in many countries, stemming from concerns over BSE transmission, despite no evidence linking insects to prion diseases (Hancz et al. 2024; Gao et al. 2024). Nonetheless, as with monogastrics, initial research on ruminants focused on insect meals within vitro models, followed by recent in vivo trials (Bellezza Oddon et al. 2025). The following subsections aim to present the current knowledge on the use of insects in ruminant diets, categorised into in vitro and in vivo studies, and to provide a picture of the effectiveness of insect-based feeds based on what science has done so far.

4.1 | Evidence From In Vitro Studies

4.1.1 | In Vitro Gas Production and Fermentation Profile

Table 1 summarises the in vitro experiments reviewed, which assess the impact of various insect species on ruminal fermentation. The use of insect meals, whether full-fat or defatted, is often associated with a reduction in both the potential and volume of gas production. For example, full-fat housefly larvae and silkworm pupae meals (at inclusion levels of 5%, 10%, 20%, and 40%) were evaluated as alternative protein sources to replace SBM in a ruminant diet consisting of 60% grass and 40% SBM. Both tested meals, when included at high levels (40%), significantly reduced total gas production (mL/g DM) with reductions of >20% for housefly larvae and >7% for silkworm pupae (Ahmed et al., 2025). Similarly, Ahmed and Nishida (2023) showed that increasing the inclusion level (beyond 20%) of either full-fat cricket or silkworm meal led to a significant reduction in the total gas production (a decrease of 21.85% and 23.82%, respectively) and volatile fatty acids (VFA) production (a decrease of 9.10% and 8.25%, respectively), due to the high fat content of the meals; however, both tested insects linearly increased $\text{NH}_3\text{-N}$ concentration by 53.76% for cricket meal and 66.25% for silkworm meal. This is an inclusion of both cricket and silkworm meals at 10% of the diet did not adversely affect in vitro dry matter digestibility (IVDMD) (Ahmed et al. 2021). Replacing full-fat SBM with cricket meal in a 60:40 forage:concentrate diet reduced the potential of gas production, acetate (C_2), as well as the acetate and propionate ($\text{C}_2\text{:C}_3$) ratio (Phesatcha et al. 2022).

Substitution of 50–100% SBM with full-fat *Hermetia illucens* larvae meal was associated with reductions of in vitro organic and

dry matter digestibility (IVOMD and IVDMD) (Jayanegara et al. 2017). Similarly, Renna et al. (2022) assessed full-fat insect meals from eight insect species using rumen fluid from cannulated sheep, and lower IVOMD values were reported for most insect meals (except *Blatta lateralis*) compared to plant-based protein sources such as SBM, sunflower, and rapeseed meals. Also, Robles-Jimenez et al. (2025b) showed that dietary full-fat mealworm (at 60 g/kg DM) reduced in vitro rumen gas production. However, total mixed rations (TMRs) containing 20% and 40% defatted *Hermetia illucens* larvae as a substitute for SBM resulted in higher cumulative gas production compared to a control (without insect meal) (Kahraman et al. 2023). Interestingly, the inclusion of silkworm pupae meal increased IVDMD without negatively affecting total VFA production. In contrast, full-fat housefly larvae reduced both IVDMD and total VFA production compared to a control group (Ahmed et al. 2025). These authors attributed the improved IVDMD to the higher rumen-degradable protein content of silkworm pupae meal, as evidenced by the elevated $\text{NH}_3\text{-N}$ concentrations observed in these treatments. Conversely, the decrease in IVDMD with housefly larvae meal was attributed to its high chitin content, which is known to be poorly degraded by rumen microorganisms (Ahmed et al. 2025).

The high protein content of insects supports their use as an alternative protein source. Assessing their digestibility in ruminants requires evaluating both ruminal degradation and intestinal absorption of undegraded protein (Torral et al. 2022). As most dietary protein is converted in the rumen to ammonia for microbial use, interest has grown in proteins that bypass the rumen and are absorbed in the intestine to improve animal performance (Renna et al. 2023). Lower ruminal $\text{NH}_3\text{-N}$ concentrations were observed when full-fat insect meals were compared with plant meals, as reported by Renna et al. (2022), consistent with findings from a previous comparison between *H. illucens* larvae meal and SBM by Jayanegara et al. (2017). Such a result would be considered beneficial for ruminant nutrition, provided that the intestinal digestibility of rumen-undegraded protein is high, as thoroughly reviewed by Renna et al. (2023). Decreased in vitro ammonia in insect-added TMRs was also reported by Kahraman et al. (2023). These authors hypothesised that lower ruminal $\text{NH}_3\text{-N}$ could be attributed to protein fractions of insects that are not degraded in the rumen, such as neutral detergent insoluble crude protein (NDICP) and acid detergent insoluble crude protein (ADICP). Additionally, in a recent study, the high rumen-undegradable protein content of full-fat housefly larvae meal was supported by unchanged $\text{NH}_3\text{-N}$ concentrations, suggesting limited insect protein degradation in the rumen (Ahmed et al. 2025). However, Robles-Jimenez et al. (2025b) showed higher ruminal ammonia and microbial crude protein (MCP) levels in a mealworm-based diet compared to an FM-based diet. Similarly, replacing SBM with graded levels of full-fat cricket meal enhanced ruminal $\text{NH}_3\text{-N}$ concentration (Phesatcha et al. 2022). This was attributed by the authors to the high protein content of insect meals, the ability of ruminal microbes to synthesise stimulatory compounds and microbial protein, and potential shifts in the abundance of proteolytic bacteria (Robles-Jimenez et al. 2025b; Phesatcha et al. 2022).

A study (Renna et al. 2025) revealed that drying full-fat HI and TM meals at 30–70°C minimally affected in vitro ruminal digestibility and fatty acid profiles of rumen digesta. However, protein degra-

TABLE 1 | Effect of dietary inclusion of insect-based feed on in vitro nutrient digestibility and ruminal fermentation parameters in ruminant species.

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Bombyx mori</i>	Pupae/Oil (solvent- extracted)	Holstein- Friesian crossbred bulls	Not specified	2, 4, 6, 8 and 10%	- Total gas production decreased with silkworm pupae oil supplementation at 4% of the diet. - CH₄ production was reduced by 22.8% with 2% oil supplementation; however, an increase in oil supplementation level up to 4–6% did not reveal a different reduction in CH₄ production. - Insect oil at a level of 8–10% decreased in vitro dry matter digestibility.	Thirumalaisamy et al. (2020)
<i>Bombyx mori</i>	Pupae/Full-fat meal	Holstein cows	Soybean meal	5%, 10%, 20% and 40%.	Silkworm meal could fully replace SBM at up to 40% inclusion in the diet, enhancing IVDMD without compromising fermentation while reducing CH₄ yield by 20%, providing a notable environmental benefit.	Ahmed et al. (2025)
<i>Musca domestica</i>	Larva/Full-fat meal	Holstein cows	Soybean meal	5%, 10%, 20% and 40%.	Housefly meal could partially replace SBM at up to 10% since it exerts no negative effects on fermentation characteristics but reduced CH₄ production by 15.5%, whereas higher inclusion levels adversely affected rumen fermentation.	Ahmed et al. (2025)
<i>Bombyx mori</i>	Pupae/Full-fat meal	Holstein cows	Not specified	10, 20, 30 and 40%	- Cricket meal linearly reduced total gas production, while the proportion of CH₄ and CO₂ was not affected. - The IVDMD and VFA production decreased linearly beyond the inclusion level of 20%. - Cricket meal linearly increased the concentration of NH₃-N.	Ahmed and Nishida (2023)

(Continues)

TABLE 1 | (Continued)

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Holstein cows	Not specified	10, 20, 30 and 40%	- Silkworm meal linearly reduced total gas production, while the proportion of CH₄ and CO₂ was not affected. - The IVDMD and VFA production decreased linearly beyond the inclusion level of 20%. - Silkworm meal linearly increased the concentration of NH₃-N.	Ahmed and Nishida (2023)
<i>Bombyx mori</i>	Pupae/Oil (solvent-extracted)	Holstein bulls	Not specified	0.5, 1, 2, 4 and 5%	- Silkworm pupae oil up to a 2% level on total gas production; however, beyond 2% has shown a reduction in total gas production. - A graded decrement in CH₄ production was recorded with increasing levels of silkworm pupae oil. - Protozoal populations were decreased from 10 to 51.5% with graded levels of insect oil.	Thirumalaisamy et al. (2020)
<i>Notonecta</i> sp.	Subadult stage/Full-fat	Suffolk male sheep	Compared with fish meal and soybean meal	6%	- Waterfly meal did not change DM degradation and MCP production. - No differences were found for enteric methane production. Waterfly meal inclusion produced the lowest NH₃-N at 12 and 24 h after in vitro incubation.	Robles Jimenez et al. (2024)
<i>Tenebrio molitor</i>	Larva/Oil (solvent-extracted)	Crossbred Cow	Not specified	6%	- The addition of insect oil reduced the CH₄ emission without altering total VFA concentration. - The oils had no significant effect on ruminal ammonia concentration. - Generally, the addition of insect oil reduced the DM and OM digestibility of the substrates.	Jayanegara et al. (2020)

(Continues)

TABLE 1 | (Continued)

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Gryllus bimaculatus</i>	Nymph/Oil (solvent- extracted)	Crossbred Cow	Not specified	6%	- The addition of insect oil reduced the CH₄ emission without altering total VFA concentration. - The oils had no significant effect on ruminal ammonia concentration. - Generally, the addition of insect oil reduced the DM and OM digestibility of the substrates.	Jayanegara et al. (2020)
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Dairy steers	Soybean meal	0%, 25%, 50%, 75% and 100% (Substitution level)	- In vitro DM degradability and the concentration of propionic acid were increased, while the potential gas production, acetate, and protozoal population were reduced by increasing cricket meal inclusion. - Rumen CH₄ production was mitigated with increasing levels of insect meal for SBM.	Phesatcha et al. (2022)
<i>Acheta domesticus</i>	Adult/Full-fat meal	Adult ewes	Soybean meal	10% FM of diet	- Replacing dietary SBM with cricket meal did not affect the ruminal disappearance of DM, N, and NDF. - The replacement had no negative effects on rumen pH or NH₃-N concentrations, but resulted in lower total and individual (i.e., acetate, propionate, butyrate, and minor) VFA concentrations. - Insect meal modulated a fatty acid profile of the rumen digesta (e.g., it increased trans-11 18:1 and cis-9 trans-11 CLA concentrations, with only a small variation in the trans-10:trans-11 18:1 ratio).	Hervás et al. (2024)

(Continues)

TABLE 1 | (Continued)

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Hermetia illucens</i>	Larvae/oil	Thai native steers	Not specified	0, 2, 4 and 6% of DM	- Insect oil (2% and 4%) did not affect the degradability of DM after 12 and 24 h of incubation, whereas increasing the concentration of insect oil in the concentrate to 6% reduced the DM degradability. - Supplementing 4% of Black Soldier Fly larvae oil resulted in a significant reduction in ruminal CH₄ concentration.	Prachumchai and Cherdthong (2023)
<i>Hermetia illucens</i>	Larvae/full-fat and defatted meal	Male sheep	Not specified	Not specified	- Drying temperature (30–70°C) had minimal effects on rumen digestibility and FA biohydrogenation of full-fat insect meals. - Defatted insect meals increased total gas, VFA, and CH₄ production during ruminal fermentation. - Defatted meals enhanced the proportions of saturated and branched-chain FAs in rumen digesta. - Defatted insect meals showed higher ruminal digestibility compared to full-fat meals.	Renna et al. (2025)
<i>Hermetia illucens</i>	Larvae/Full-fat meal	Holstein cows	Soybean meal	20% and 40% (Substitution level)	Replacing SBM with BSFL meal reduced ruminal NH₃-N, whereas increasing total VFA levels and IVDMD	Kahraman et al. (2023)
<i>Hermetia illucens</i>	Larvae/Full-fat meal	Holstein cows	Soybean meal	5, 10 and 15% (Substitution level)	- Dietary inclusion of 5 and 10% BSFLmeal enhanced gas production, while 15% inclusion reduced it. - Insect meal (at a level of 15%) mitigated CH₄ emission at 6 h and 12 h of incubation.	Lu et al. (2024a)

(Continues)

TABLE 1 | (Continued)

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Texel male sheep	soybean meal, rapeseed meal, and sunflower meal	Meal samples incubated	- Insect meals led to a significantly lower total gas production, methane production, volatile FA production, and in vitro organic matter disappearance. - The FA profile of the rumen digesta is rich in n-6 polyunsaturated FA	Renna et al. (2022)
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Texel male sheep	soybean meal, rapeseed meal, and sunflower meal	Meal samples incubated	- Insect meals led to a significantly lower total gas production, methane production, volatile FA production, and in vitro organic matter disappearance. - The FA profile of the rumen digesta is rich in n-6 polyunsaturated FA	Renna et al. (2022)
<i>Musca domestica</i>	Larvae/Full-fat meal	Texel male sheep	soybean meal, rapeseed meal, and sunflower meal	Meal samples incubated	- Insect meals led to a significantly lower total gas production, methane production, volatile FA production, and in vitro organic matter disappearance. - The FA profile of the rumen digesta is rich in n-6 polyunsaturated FA.	Renna et al. (2022)
<i>Hermetia illucens</i>	Larvae/Full-fat meals	Rams	Soybean meal	Meal samples incubated	- There were no significant differences in ruminal degradability (e.g., a* and c* parameters) among all treatments. - The CP degradability of black soldier fly larvae meal was significantly higher than that of full-fat soybeans.	Lu et al. (2024b)
<i>Hermetia illucens</i>	Larvae/Full-fat meals	Not specified	Soybean meal	50% (Substitution level)	- Insect meal resulted in lower ruminal ammonia concentration, in vitro DM, and OM digestibility. - Diet supplemented with black soldier fly meal produced lower CH₄	Jayanegara et al. (2017)

(Continues)

TABLE 1 | (Continued)

Insect	Growth stage/ Insect form	Rumen donors	Replaced meal	Inclusion/ Substitution level	Main results	Reference
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Suffolk lambs	Soybean meal and fish meal	6% DM of diet	Total gas production was lower, while DM disappearance and MCP production were higher, for the insect meal diet when compared to the FM diet, while the SBM diet showed intermediate values.	Robles-Jimenez et al. (2025a)
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Suffolk × Texel ewes	A combination of mealworm and a natural source of tannins		Increasing dietary mealworm levels were associated with an increase in $\text{NH}_3\text{-N}$ concentrations and a reduction in CH_4 production.	Gonzalez-Ronquillo et al. (2025)

Abbreviations: CH_4 , methane; CLA, conjugated linoleic acid; CO_2 , carbon dioxide; CP, crude protein; DM, dry matter; EE, ether extract; FA, fatty acid; FM, fish meal; IVDMD, in vitro dry matter digestibility; MCP, microbial crude protein; N, nitrogen; NDF, neutral detergent fibre; $\text{NH}_3\text{-N}$, ammonia nitrogen; OM, organic matter; SBM, soybean meal; VFA, volatile fatty acids.

dation was slightly reduced at higher temperatures, as indicated by decreased ammonia production, potentially enhancing intestinal protein flow for ruminant production. Defatting improved in vitro ruminal digestibility, evidenced by increased total gas and VFA production. Conversely, methane (CH_4) production rose due to enhanced fermentation and reduced fat content, which typically suppresses methanogenesis. Additionally, defatting lowered polyunsaturated fatty acid (PUFA) proportions while increasing saturated fatty acid (SFA) and branched-chain fatty acid (BCFA) levels, potentially impacting milk and meat lipid quality. Based on current evidence, the negative impacts of high insect meal inclusion on in vitro gas yield mainly relate to the high lipid and chitin contents in insect meals (Renna et al. 2023). Elevated levels of unsaturated fatty acids may exert toxic effects on ruminal cellulolytic microbes (Phesatcha et al. 2022). Additionally, chitin is poorly degradable in the rumen, further limiting nutrient fermentability (Jayanegara et al. 2017). However, higher gas production in some reports suggests implications of insect meals on in vitro digestibility may likely be influenced by factors such as overall diet composition and the forage-to-concentrate ratio, rather than by insect inclusion alone.

4.1.2 | In Vitro Methane Production

Generally, dietary inclusion of insect-based feeds mitigated CH_4 emissions per unit of feed intake by 12–30% in ruminants (Kichamu et al. 2025). In an in vitro bovine trial, Ahmed et al. (2021) reported that replacing 25% of SBM with full-fat adult field cricket or silkworm pupae meals reduced CH_4 production by 18% and 16%, respectively. Similarly, CH_4 -suppressing effects of insect meals were demonstrated by Phesatcha et al. (2022), with CH_4 reductions of 18% and 16% observed following the inclusion of 25% full-fat cricket (*Gryllus bimaculatus*) and full-fat

silkworm pupae meals, respectively. Using ewes as rumen donors, Gonzalez-Ronquillo et al. (2025) also highlighted that increasing dietary full-fat yellow mealworm levels when replacing *Acacia farnesiana* in the diet in ratios ranging from 20:80 to 100:0 (on a DM basis) was associated with a significant reduction in CH_4 production. Dietary supplementation with 2%, 4%, 6%, 8% and 10% silkworm pupae oil has been evaluated for its effects on in vitro fermentation kinetics, enteric methane emissions, and methanogen diversity in sheep (Thirumalaisamy et al. 2022b). Results indicated a decrease in total gas production at supplementation levels above 4%. Notably, a 22.8% reduction in CH_4 production (mL/g) was observed at the lowest supplementation level of 2% compared to the control. Increasing the supplementation to 4–6% did not result in any statistically significant additional reduction in CH_4 production. A recent study (Ahmed et al. 2025) also showed that the CH_4 production decreased with full-fat housefly larvae inclusion at 20% and 40%, by 12.2% and 20.3%, respectively. Complete replacement of SBM with full-fat silkworm pupae also reduced CH_4 yield (mL/g DM) by 20.8% (Ahmed et al. 2025). Another study (Jayanegara et al. 2020) using insect oils at 5% DM in two kinds of diets, high forage (70% forage: 30% concentrate) and high concentrate (30% forage: 70% concentrate), confirmed the CH_4 -mitigatory effect of insect-based feeds. The inclusion of 4% black soldier fly larvae oil in a 40:60 forage-to-concentrate diet was found to reduce CH_4 emissions when beef rumen fluid was used as the inoculum (Prachumchai and Cherdthong 2023).

Although some studies have reported no significant effect of insect-based feeds on in vitro CH_4 production (Hanönü et al. 2024; Kahraman et al. 2023), current scientific evidence recognises insects as a promising nutritional strategy for mitigating enteric CH_4 emissions in ruminants. The extent of this mitigatory effect appears to depend on inclusion level, processing method,

insect species, and the composition of the basal diet. Although the exact mechanism of insects on methanogenesis remains unclear, this is mainly attributed to the following biochemical mechanisms: (1) suppression of methanogens by chitin, which disrupts cell membrane function and competes for key substrates (Jayanegara et al. 2017); (2) inhibition of protozoa by long-chain polyunsaturated fatty acids (PUFAs), which limits hydrogen transfer needed for methanogenesis (Renna et al. 2022; Kichamu et al. 2025); and (3) enhanced nitrogen utilisation, which reduces fermentable substrate availability and subsequent ammonia and methane production (Kichamu et al. 2025).

4.2 | Evidence From In Vivo Studies

4.2.1 | Animal Performance, Intake and Digestibility

Although in vivo research on insect-based feed applications in ruminants remains comparatively scarce compared to what has been done in monogastric species, it is gaining momentum. Table 2 and Figure 5 provide a summary of the existing scientific literature on in vivo experiments in ruminants, highlighting the key findings from each study.

The first in vivo report on the use of insects in ruminants was published by Astuti et al. (2019), who investigated the effects of including full-fat adult cricket meal (*Gryllus bimaculatus*) in the diets of pre- and post-weaning goat kids. The results showed that, in pre-weaning goats, nutrient intake increased and growth performance was comparable to those of kids fed goat milk, although feed efficiency was lower. In post-weaning kids, replacing 50–100% of SBM with 15–30% full-fat cricket meal in the concentrate had no negative impact on feed intake, growth, feed conversion, or rumen fermentation. Subsequent, more targeted studies have investigated specific aspects, for example, in a 21-day trial, Suffolk lambs fed 6% full-fat *Notonecta* sp. (water fly) meal showed no differences in dry matter intake (DMI), nitrogen retention, or microbial protein synthesis compared to those fed SBM or FM; however, digestibility of DM and organic matter (OM) was reduced (Robles Jimenez et al. 2024). Similarly, Odeon et al. (2025) found that a 10% inclusion of defatted BSFL meal in Merino lambs for 50 days maintained DMI, average daily gain (ADG), and feed conversion ratio (FCR), supporting its use as a full replacement for SBM without performance penalties (Odeon et al. 2025).

In another study, Sahib et al. (2025) showed that feeding crossbred female calves with full-fat silkworm pupae meal replacing 20% and 50% of FM for 90 days had no adverse effects on animal health, as haematological and biochemical indices remained unchanged, supporting the safety of this insect-based ingredient. In Thai native cattle, Phesatcha et al. (2023) observed improved CP and fibre digestibility as SBM was gradually replaced with full-fat cricket meal pellets, with DMI remaining unaffected. This aligns with Khonkhaeng et al. (2025), who found that a 12% inclusion of full-fat cricket meal in beef cattle diets maintained DMI while enhancing CP digestibility and resulting in a 55.7% increase in ADG and a 32.9% improvement in FCR compared to a conventional SBM diet.

Contrasting effects have also been noted. Robles-Jimenez et al. (2025a) found that full-fat TM meal at 6% DM in lamb diets reduced DMI and ADG compared to SBM, but digestibility of DM and OM improved, final body weight was unaffected, and nitrogen balance ranked FM > TMM > SBM. Additionally, in sheep, the inclusion of silkworm pupae oil at 2% of DMI, administered daily or biweekly over 180 days, did not affect DM and CP intakes but enhanced energy intake. Also, CH₄ emissions were reduced by 23–25%, indicating a dual benefit for nutrition and environmental sustainability (Thirumalaisamy et al. 2022a).

Robles-Jimenez et al. (2025b) observed that SBM supported higher ADG and better carcass traits compared to full-fat TM meal, although TM meal-fed lambs maintained acceptable growth and health outcomes. Ayaz et al. (2023) showed that replacing 25% of concentrate with mealworm frass improved weight gain (2.9 kg over 6 weeks) and reduced feed refusal (6.3%), while a 50% replacement led to reduced intake and performance, underscoring a potential threshold beyond which insect frass may become counterproductive. Carrasco and Drewery (2024) found that, although SBM stimulated higher forage intake compared to defatted TM larvae, BSFL, and their blend, digestibility and VFA production remained unaffected, indicating that insect meals can match conventional supplements in beef cattle. Fukuda et al. (2022) also confirmed that full-fat BSFL-supplemented diets enhanced forage intake and total digestible OM intake in steers, without compromising nutrient digestibility.

As discussed above, the current scientific evidence, albeit limited, on the effects of insect-derived products on the growth performance of ruminants is not univocal. Taken together, findings indicate that insect-based feeds can support or even enhance ruminant performance under certain conditions; however, their efficacy appears to depend heavily on insect species, processing methods, and inclusion level. This complexity underscores the importance of further comparative trials to establish optimal formulations and boundaries of use.

4.2.2 | Rumen Fermentation and Microbial Populations

Rumen fermentation is a key determinant of ruminant productivity, and insect-derived feedstuffs (rich in fat and chitin) have been shown to modulate fermentation dynamics and microbial ecology. However, current research findings remain inconclusive, and definitive conclusions will require further complementary studies. Below, we summarise the findings from in vivo studies on rumen fermentation and the mechanisms driving these effects.

Rashmi et al. (2022) found that replacing SBM with defatted silkworm pupae meal (up to 30%) did not affect rumen pH, NH₃-N, VFA, MCP synthesis, or digestibility. Similar findings were reported by Khonkhaeng et al. (2025), where full-fat cricket meal inclusion at a level of 12% DM supported improved CP digestibility and animal performance without altering fermentation parameters. A recent study found that BSFL meal at 10% in lamb diets did not influence ruminal pH, VFA, or microbial fermentation, further validating its safety (Odeon et al. 2025). In line with these reports, Carrasco and Drewery (2024), using

TABLE 2 | Effect of dietary inclusion of insect-based feed on in vivo performance, nutrient digestibility and ruminal fermentation parameters in ruminant species.

Insect	Insect growth stage/form	Ruminant species	Replaced meal	Inclusion/Substitution level	Trial length	Main results	Reference
<i>Bombyx mori</i>	Pupae/Full-fat meal	Crossbred calves	Fish meal	0, 25 and 50%	90 days	Replacing FM with silkworm meal in the calf starter ration up to 50% did not change haemato-biochemicals (i.e., Hb, PCV, RBC, WBC, Glu, ALT, AST and BUN) and oxidative stress indicators (i.e., SOD, GPx, CAT and MDA).	Sahib et al. (2025)
<i>Bombyx mori</i>	Pupae/Oil (solvent-extracted)	Male sheep	Not specified	2% of DMI	180 days	- Supplementing 2% silkworm oil did not affect DMI, and CP intake increased the energy intake in sheep. - Silkworm oil also enhanced body weight gain and average daily gain. - Feeding insect oil either daily or biweekly reduced methane emission by 23–25%. - Oil supplementation decreased the numbers of total protozoa, Entodiniomorphs, and Holotrichs without a change in the rumen archaea.	Thirumalaisamy et al. (2022b)
<i>Bombyx mori</i>	Pupae/defatted meal	Crossbred steers	Soybean meal	0, 10, 20, and 30% (Substitution level)	30 days	- Ruminal pH, NH₃-N, and total VFA were not affected. - Intake and digestibility of all nutrients (DM, OM, CP, EE, NDF, and ADF) remained unaffected by insect meal. - Blood glucose, cholesterol, ALP, SGOT, SGPT, BUN, creatinine, total protein, albumin, and globulin were unaltered.	Rashmi et al. (2022)
<i>Bombyx mori</i>	Pupae/Oil (solvent-extracted)	Male sheep	Not specified	2%	46 days	- Feeding of silkworm pupae oil at 2% of the diet did not affect nutrient intake except for EE, which showed an increase. - Apparent digestibility of OM, CP, NDF and ADF was not affected. - Insect oil decreased ruminal NH₃ concentration while total volatile fatty acid concentration remained unaffected. - A significant reduction of 17% and 20% in enteric CH₄ emission was reported with silkworm pupae oil supplementation. - Insect oil decreased total rumen protozoal numbers by 39–42%. Both entodiniomorph and holotrich numbers were also reduced.	Thirumalaisamy et al. (2020)

(Continues)

TABLE 2 | (Continued)

Insect	Insect growth stage/form	Ruminant species	Replaced meal	Inclusion/Substitution level	Trial length	Main results	Reference
Notonecta sp.	Subadult stage/Full-fat	Suffolk male sheep	Compared with fish meal and soybean meal	6% DM of diet	21 days	- DM intake was similar among insect, SBM and FM groups. However, the digestibility of DM and OM in the waterfly meal group was lower than that of SBM but similar to FM. - Lambs fed the insect diet showed a higher growth rate than those fed FM and SBM. - Nitrogen intake and faecal N excretion remained unaffected; however, urinary N excretion tended to decrease with NT feeding.	Robles Jimenez et al. (2024)
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Goat	Soybean meal	15% and 30% DM of the diet	60 days	Dietary inclusion of cricket meal at levels of up to 30% in the concentrate portion of diets for growing goats led to a favourable palatability, with no adverse impacts on ruminal fermentation profiles and comparable performance relative to control rations.	Astuti et al. (2019)
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Thai native beef	Soybean meal	0%, 33%, 67% and 100% (Substitution level)	21 days	- Replacing SBM with cricket meal did not affect DMI, while the digestibility of CP, NDF, and ADF was enhanced. - Insect substitution increased production of VFA, particularly propionate, and enhanced microbial protein synthesis. - Feeding cricket meal resulted in lower protozoal populations and CH₄ production.	Phesatcha et al. (2023)
<i>Gryllus bimaculatus</i>	Adult/Full-fat meal	Thai Beef Cattle	Soybean meal	12% DM of diet	90 days	- DMI and digestibility of nutrients (DM, OM, NDF, and ADF) were not affected; however, substituting cricket meal with SBM enhanced CP digestibility. - Blood metabolite and rumen fermentation parameters remained unaffected by diets. - Replacing SBM with cricket meal increased final BW by 10.7% and ADG by 55.7%.	Khonkhaeng et al. (2025)
<i>Hermetia illucens</i>	Larvae/defatted meal	Male Merino lambs	Soybean meal	10% DM of diet	50 days	- Animal performance (BW, BCS, ADG, DMI and FCR) did not differ between SBM and Black Soldier Fly Larvae Meal. - Stress indicators (blood cortisol, plasma proteins and glucose levels) remained unaffected by diets. - Ruminal pH and N-NH₃ concentration, total VFA concentration, and acetate, propionate, and butyrate percentages did not alter with insect meal.	Odeon et al. (2025)

(Continues)

TABLE 2 | (Continued)

Insect	Insect growth stage/form	Ruminant species	Replaced meal	Inclusion/Substitution level	Trial length	Main results	Reference
<i>Hermetia illucens</i>	Larvae/defatted meal	Qianbei goat	Soybean meal	10% DM of diet	60 days	- The slaughter rate and carcass weight of the animals fed black soldier fly larvae meal were lower than the control. - The moisture, DM, CP, ash, amino acids, and mineral content of the muscles remained unaffected. - The individual unsaturated fatty acids and total unsaturated fatty acids increased with insect meal. - Replacing SBM with insect meal reduced the antioxidant capacity of meat. - Average daily milk yield of insect-fed cows was slightly higher than the control. - Insect oil did not change the composition and quality of milk as well as blood parameters (e.g., TP, ALB, GLB, BUN, AST, ALT, ALP, Ca and P)	Lu et al. (2024c)
<i>Hermetia illucens</i>	Larvae/oil	Dairy cow	Not specified	10 and 100 g/head/day	176 days	- Average daily milk yield of insect-fed cows was slightly higher than the control. - Insect oil did not change the composition and quality of milk as well as blood parameters (e.g., TP, ALB, GLB, BUN, AST, ALT, ALP, Ca and P)	Nekrasov et al. (2022)
<i>Hermetia illucens</i>	Larvae/oil	Dairy cow	Hydrogenated palm fat	3.4% DM of diet	50 d	- No effect on nutrient intake or apparent total-tract digestibility. - Higher milk production in HIO-fed cows (+0.82 kg/cow/day) and improved feed efficiency. - No significant differences in milk composition or metabolic status of cows. - Enhanced antioxidant status in HIO-fed cows, with lower reactive oxygen metabolite concentrations.	Rastello et al. (2025)
<i>Hermetia illucens</i>	Larvae/Full-fat meals	Male goats	Not specified	5%, 10% and 15% DM of diet	Not specified	- No significant effect on the growth performance of goats. - Digestibility of DM, OM, CP, NDF and ADF decreased with increasing insect meal. - Insect meal improved serum antioxidant status, as indicated by increased SOD activity. - Insect supplementation did not alter ruminal microbiology.	Lu et al. (2025)
<i>Hermetia illucens</i>	Larvae/Full-fat meals	Sheep	Soybean meal	2.5% and 5% DM of diet	84 days	BSFL have the potential to replace soybean meal in sheep diets without negatively impacting performance or haematological profiles.	Rahman et al. (2021)

(Continues)

TABLE 2 | (Continued)

Insect	Insect growth stage/form	Ruminant species	Replaced meal	Inclusion/Substitution level	Trial length	Main results	Reference
<i>Hermetia illucens</i>	Larvae/Full-fat meals	Steers	Soybean meal	as a protein supplement	14 days	• Insect supplementation stimulated forage OM intake, while total digestible OM intake reduced. • Replacing SBM with Black soldier fly larvae meal did not affect the digestibility of DM, OM, or NDF as well as ruminal ammonia-N, total volatile fatty acids, or ruminal pH.	Fukuda et al. (2022)
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Steers	Soybean meal	TM, HI, and their 50:50 blend	14 days	• Steers receiving insect supplements consumed and digested more OM compared to those in the control group.	Carrasco and Drewery (2024)
<i>Hermetia illucens</i>	Larvae/defatted meal					• Diet digestibility was not significantly different across protein supplements.	
<i>Tenebrio molitor</i>	Larvae/Frass	Sheep	Commercial concentrate	0, 25, and 50%	60 days	• Dietary inclusion of mealworm frass increased growth and weight gain in sheep. • Mealworm frass increased the palatability and total intake of the concentrate feed.	Ayaz et al. (2023)
						• Feeding mealworm frass increased the volume of WBC and RBC and raised the serum phosphorus level.	
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Suffolk lambs	Soybean meal and fish meal	6% DM of diet	60 days	• Mealworm-fed lambs showed lower ADG when compared to both the SBM-fed and the FM-fed lambs; however, DMI of the insect group was similar to the FM group. • The hot and cold carcass weights and yields were lower in the TMM group compared with the SBM group but similar to the FM group. • The dietary mealworm did not affect meat pH, colour, texture, water loss or contents of fat, protein and moisture.	Robles-Jimenez et al. (2025b)

(Continues)

TABLE 2 | (Continued)

Insect	Insect growth stage/form	Ruminant species	Replaced meal	Inclusion/Substitution level	Trial length	Main results	Reference
<i>Tenebrio molitor</i>	Larvae/Full-fat meals	Suffolk lambs	Soybean meal and fish meal	6% DM of diet	30 days	- DM intake of mealworm-fed lambs was comparable to that of FM-fed lambs but lower than that of SBM-fed lambs. - ADG was reduced in the insect-fed lambs, while the FBW remained unaffected. - Total tract apparent digestibility of DM and OM was higher in the mealworm group compared to SBM. - Ruminal morphometric indexes (i.e., papillae length and width, absorption area, and thickness of mucosa, submucosa and muscular layers) were not affected by diet. - Histopathological features in the rumen, intestine, and liver were not affected by mealworm feeding.	Robles-Jimenez et al. (2025a)

Abbreviations: ADF, acid detergent fibre; ADG, average daily gain; ALB, albumin; ALP, alkaline phosphatase; ALT, alanine aminotransferase; AST, aspartate aminotransferase; BCS, body condition score; BUN, blood urea nitrogen; BW, body weight; CAT, catalase; CP, crude protein; DM, dry matter; DMI, dry matter intake; EE, ether extract; FBW, final body weight; FCR, feed conversion ratio; FM, fish meal; GLB, globulin; GLU, glucose; GPx, glutathione peroxidase; Hb, haemoglobin; HIO, *Hermetia illucens* oil; IVDMD, in vitro dry matter digestibility; MDA, malondialdehyde; NDF, neutral detergent fibre; NH₃-N, ammonia nitrogen; OM, organic matter; P, phosphorus; PCV, packed cell volume; RBC, red blood cell; SBM, soybean meal; SGOT, serum glutamic oxaloacetic transaminase; SGPT, serum glutamic pyruvic transaminase; SOD, superoxide dismutase; TP, total protein; VFA, volatile fatty acids; WBC, white blood cell.

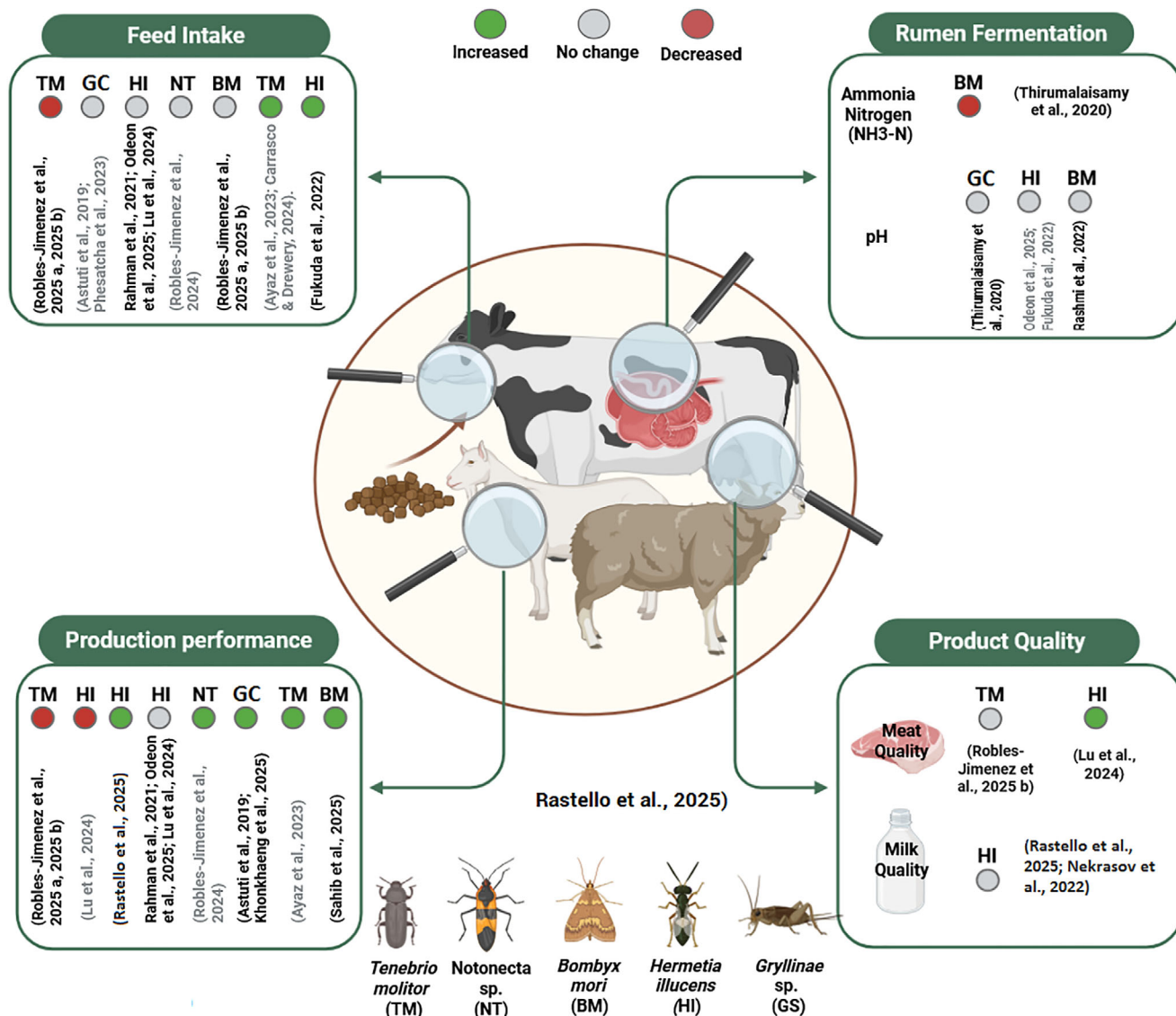


FIGURE 5 | How diets containing insect-derived products affect ruminant performance (created in BioRender).

defatted TM larvae, BSFL, and their 50:50 blend, showed no significant differences in VFA concentration or rumen fermentation metrics versus SBM. Likewise, full-fat BSFL supplementation in beef steers improved intake without altering VFA profiles, pH, or NH₃-N, confirming stable fermentation parameters (Fukuda et al. 2022).

However, in lambs fed full-fat water flea meal (*Notonecta* sp.), NH₃-N concentrations were lower at 12 and 24 h post-feeding, though microbial protein synthesis and CH₄ emissions were unaffected (Robles Jimenez et al. 2024). Also, another study on full-fat house cricket meal in cannulated sheep revealed lower total and individual VFA, attributed to high fat content. House cricket meal also modified the rumen fatty acid profile by increasing trans-11 18:1 and total CLA, with minimal disruption to biohydrogenation (Hervás et al., 2024). In sheep, silkworm pupae oil supplementation decreased populations of total protozoa, *entodiniomorphs*, and *holotrichs* without altering the archaeal community (Thirumalaisamy et al. 2022b).

Contrary to the abovementioned results, Phesatcha et al. (2023) showed that feeding full-fat cricket meal pellets increased NH₃-N, total VFA (especially propionate), and MCP synthesis in beef cattle. Protozoa counts and CH₄ emissions were simultaneously reduced, highlighting the fermentation benefits of cricket meal (Phesatcha et al. 2023). Also, BSFL fat supplementation in dairy cows increased total VFA and rumen infusoria counts while lowering rumen pH. The positive shift in fermentation indicators was accompanied by higher milk fat yield (Nekrasov et al. 2022). In a recent study, Robles-Jimenez et al. (2025b) reported that feeding full-fat TM meal to lambs led to lower epithelial keratinisation in the ruminal dorsal sac compared to SBM, with no major differences in rumen or intestinal morphology, suggesting a milder effect on rumen epithelial health.

Collectively, these results illustrate both the promise and the complexity of using insect-based ingredients to modulate rumen fermentation. While many studies report metabolic neutrality or benefits, others indicate that specific insect traits (especially lipid levels and processing) can alter microbial activity or fermentation

patterns. Further mechanistic studies are required to untangle these interactions.

4.2.3 | Product Quality

In a study on Qianbei goats, the effects of replacing 10% SBM in the diet with either untreated or heat-treated BSFL were evaluated over 30 days, focusing on meat quality traits (Lu et al., 2024b). While basic muscle composition (moisture, protein, ash, amino acids, and most minerals) remained unaffected, ether extract content increased with the heat-treated BSFL. Both forms of BSFL reduced carcass yield and dressing percentage. Meat from the untreated insect meal group also exhibited higher drip loss and pH at 45 min postmortem, indicating reduced quality. Fatty acid profiles shifted, with heat-treated BSFL showing an increase in unsaturated fatty acid content and a decrease in SFA level, likely due to the formation of protective starch-lipid complexes during heat treatment, compared to the control group. The untreated insect meal also decreased the PUFA/SFA ratio and increased the n-6/n-3 ratio. Antioxidant enzyme activities (CAT, GSH-Px and T-AOC) were significantly reduced in both insect-fed groups, suggesting a decline in oxidative stability. Overall, heat-treated BSFL meal showed relatively better outcomes than untreated BSFL but still had some adverse effects compared to the SBM control (Lu et al., 2024c). Nekrasov et al. (2022) evaluated the inclusion of BSFL fat in dairy cow diets, focusing on milk composition and fatty acid profile. Milk samples were collected at multiple time points during a 176-day trial. BSFLF supplementation at 100 g/head/day exhibited a significant 8% increase in milk fat. Notably, BSFL fat did not evoke substantial changes in the milk fatty acid profile; only minor tendencies toward increased MUFA and PUFA were observed, while lauric acid (C12:0) remained the predominant FA (~58.9%). These compositional changes, alongside stable protein and lactose levels and unaffected somatic cell counts, suggest that while BSFL fat can be included without compromising milk or udder health, its ability to enhance milk lipid quality, particularly in terms of unsaturated fat content, is limited and highly dependent on which dietary fat it replaces.

A recent study (Robles-Jimenez et al., 2025b) demonstrated that the meat quality traits of lambs, including pH, colour (L^* , a^* and C^*), water loss, and shear force, were not significantly influenced by dietary inclusion of full-fat TM meal (at 60 g/kg DM). However, temporal changes post-mortem revealed notable dynamics in meat colour. Notably, TM-fed lambs exhibited higher b^* (yellowness) and hue angle (h) values on day 7 compared to SBM and FM groups, suggesting a transient enhancement in meat colour vividness. Despite these effects being time-limited, the data indicate that TM meal may influence specific aspects of meat visual quality, warranting further investigation into postmortem colour stability in insect-fed ruminants.

Taken as a whole, findings on product quality reflect a cautious optimism. Insects may enrich lipid profiles or affect post-mortem traits favourably; yet, in some cases, carcass metrics and oxidative stability decline. This underscores the need to optimise insect processing and inclusion levels to preserve or enhance end-product quality.

5 | Economic Implications, Availability and Feasibility

Feed constitutes the primary operating cost in ruminant farming. To formulate feed, various feedstuffs are combined to meet animal nutritional requirements at minimal cost. Adjustments to ingredient proportions or the inclusion of new raw materials can significantly affect farm profitability. From an economic perspective, the application of insect-based feeds is increasingly being adopted and gaining popularity within the ruminant feed industry. Currently, insect-based proteins are priced high, ranging from €3500 to €5500 per tonne, due to limited production quantities and elevated production costs, surpassing the costs of FM (€1000 to €1700 per tonne) and SBM (<€550 per tonne) (FAO 2022; Nunes et al. 2022). The insect sector, however, has not yet reached maturity. Global efforts are being undertaken to scale up production. Recent projections suggest that prices will remain stable during the scale-up phase, with an anticipated reduction to €2,000 per tonne upon sector maturity (FAO 2022; Gasco et al. 2023). Given the substantial price increase of conventional protein feeds, such as FM and SBM, compounded by disruptions like the COVID-19 pandemic and the Russia-Ukraine crisis, along with their adverse environmental impacts, opportunities to optimise or reduce feed costs must be thoroughly evaluated and leveraged.

A key factor for the successful integration of insect meals into ruminant feed is the availability and consistency of supply. To be used as a regular ingredient, sufficient quantities must be ensured. The required amount depends largely on the inclusion level in feed formulations, which varies according to the ruminant species. Based on current global feed production of 300 million metric tonnes (Alltech 2025), a 5–10% inclusion rate would demand 15 to 30 million metric tonnes—far exceeding current insect-based protein output. Although production is projected to grow rapidly, with a compound annual growth rate of 28.3% expected between 2022 and 2030 (reaching approximately 3,139,035 tonnes by 2030) (Hancz et al., 2024), global supply remains limited. For ruminant feed producers, consistent availability—both in quantity and quality—is essential before market entry, and investment in promotional activities for insect-containing feeds should be considered.

6 | Legal and Safety Considerations

Insects as feed ingredients may contain potentially hazardous substances, such as heavy metals, dioxins, mycotoxins, veterinary drugs, and pesticides (Gasco et al. 2023). Undesirable compounds may also be accumulated by insects through the rearing substrate (Meyer et al. 2021), with the extent of contamination being influenced by factors such as insect species, developmental stage, contaminant source, and rearing conditions. In particular, heavy metals such as lead, arsenic, mercury, and cadmium are absorbed by insects (Biancarosa et al. 2018; Gasco et al. 2023), whereas mycotoxins and polycyclic aromatic hydrocarbons do not appear to pose a significant risk (Meyer et al. 2021). Moreover, mycotoxins and certain veterinary drugs may be metabolised or degraded by insects, although the underlying metabolic pathways remain poorly understood. Therefore, further research is needed, as safety is a fundamental requirement across the entire food chain.

Under European Union (EU) regulations, insects used for feed or food are treated as farmed animals (European Commission 2009) and must be fed approved materials (EC 2022), meeting limits on contaminants (EC 2002) and pesticides (EC 2005). As insects can bioaccumulate toxins, the same standards apply to insect-based feeds. However, regulatory approaches vary significantly among countries, highlighting the need for harmonized international guidelines and mandatory hazard analyses for insect-derived feed products.

Although many consumer studies have indicated interest in this type of innovation (i.e., insect-fed livestock), certain limitations, such as social desirability bias, should be taken into account, given that these studies were largely hypothetical and conducted online without exposure to real products or prices. A deeper understanding of the key factors shaping consumer perceptions is seen as essential for advancing this change and would assist both policymakers and producers in designing effective strategies. For instance, awareness and acceptance may be increased through well-structured public campaigns and communication about animal production methods, particularly regarding environmental and sustainability benefits. Additionally, some research (e.g., Spartano and Grasso, 2021) indicates that products from insect-fed animal should be promoted alongside improved animal welfare claims, such as free-range certification. Therefore, successful adoption of this alternative feed option is believed to depend heavily on the provision of clear, trustworthy information at the point of sale, including certified labelling on packaging.

From a legislative standpoint, the global regulatory landscape for insect-based feed remains fragmented. In many high-income countries—including members of the EU, Japan, and China—insect meals are categorized as processed animal proteins (PAPs) and are subject to restrictions due to historical concerns over transmissible spongiform encephalopathies (TSEs), such as BSE (Lähteenmäki-Uutela et al. 2017; Renna et al. 2023). Conversely, in developing and emerging economies, specific legislation is often lacking, creating regulatory uncertainty. In the Americas, for example, there is currently no unified framework governing the use of insect proteins in animal feed processing or marketing (Lähteenmäki-Uutela et al. 2017).

Globally, the authorisation status of insect-derived feed varies widely. Insect oil and insect meal are explicitly authorized for ruminant feed in countries such as Mexico, Colombia, Brazil, Morocco, Algeria, Niger, Nigeria, Sudan, South Africa, Namibia, Ethiopia, India, Australia and New Zealand (Renna et al. 2023). Insect oil is permitted, but insect meal is not in nations including Russia, Finland, Sweden, Norway, Iceland, the United Kingdom, Denmark, Belarus, Estonia, Ireland, France, Spain, Italy, Romania, Ukraine and Poland (Renna et al. 2023). Countries like Egypt, Ecuador, Chile, Canada and Alaska (USA) lack specific regulatory frameworks, while others including Argentina, Iran, Japan, North Korea and Tunisia, do not authorize the use of insect oils or meals in ruminant feed at all (Renna et al. 2023).

Despite recent progress, significant gaps persist in the regulatory landscape. These include inconsistencies in policymaking, insufficient standardization and certification procedures for mass-produced insect-based feed, and a lack of interdisciplinary integration across relevant sectors such as food science, agri-

culture, animal husbandry, medicine, and socio-environmental sciences. The establishment of universal standards and certification protocols for insect farming and industrial production is therefore critical to ensure product safety, promote trade, and facilitate widespread adoption of this promising alternative protein source.

7 | Knowledge Gaps and Future Perspectives

The search for sustainable alternatives in ruminant nutrition has gained momentum in the face of growing environmental, economic and ethical concerns. Ruminant production systems, particularly in developing and climate-sensitive regions, are under increasing pressure to enhance feed efficiency while reducing ecological footprints. Among the emerging innovations, insects have garnered considerable attention as novel feed ingredients due to their high nutrient density, rapid biomass accumulation, and potential for bioconversion of organic waste. However, despite extensive exploration in monogastric nutrition, the application of insect meals in ruminants remains at an early stage. This review systematically synthesises available evidence, highlights current limitations, and explores the future potential of insects as sustainable feed solutions in ruminant systems (Figure 6).

In vitro and in vivo studies demonstrate that insect meals, such as those derived from black soldier fly larvae, crickets, and silkworm pupae, can support ruminant performance, often matching or surpassing conventional protein sources like soybean meal in terms of growth, feed efficiency, and rumen fermentation outcomes. Notably, insect-based feeds have shown a consistent ability to reduce enteric methane emissions by 12–30%, offering a dual benefit for nutrition and environmental sustainability. Furthermore, their lower ecological footprint—characterised by reduced land, water, and energy requirements compared to traditional feed sources—positions insects as a viable strategy for mitigating the environmental impact of ruminant production systems.

Despite these advantages, significant challenges and knowledge gaps persist. The high chitin content of insect meals can reduce in vitro digestibility, particularly at higher inclusion levels, due to limited rumen microbial degradation. In vivo studies reveal mixed results, with some reporting improved crude protein digestibility and animal performance, while others note reduced DMI or growth at elevated inclusion rates. Economic barriers, such as the high cost of insect meal compared to SBM and FM and limited production scalability, further hinder widespread adoption. Regulatory frameworks also vary globally, with restrictive policies in high-income countries due to concerns over bioaccumulation of contaminants like heavy metals, necessitating rigorous safety assessments and harmonised standards. Consumer acceptance remains a critical hurdle, as cultural perceptions and lack of familiarity with insect-fed livestock products may limit market uptake, particularly in regions unaccustomed to entomophagy.

To fully realise the potential of insect-based feeds, future research must address these gaps through a multidisciplinary approach. Longitudinal studies are needed to evaluate the long-term effects

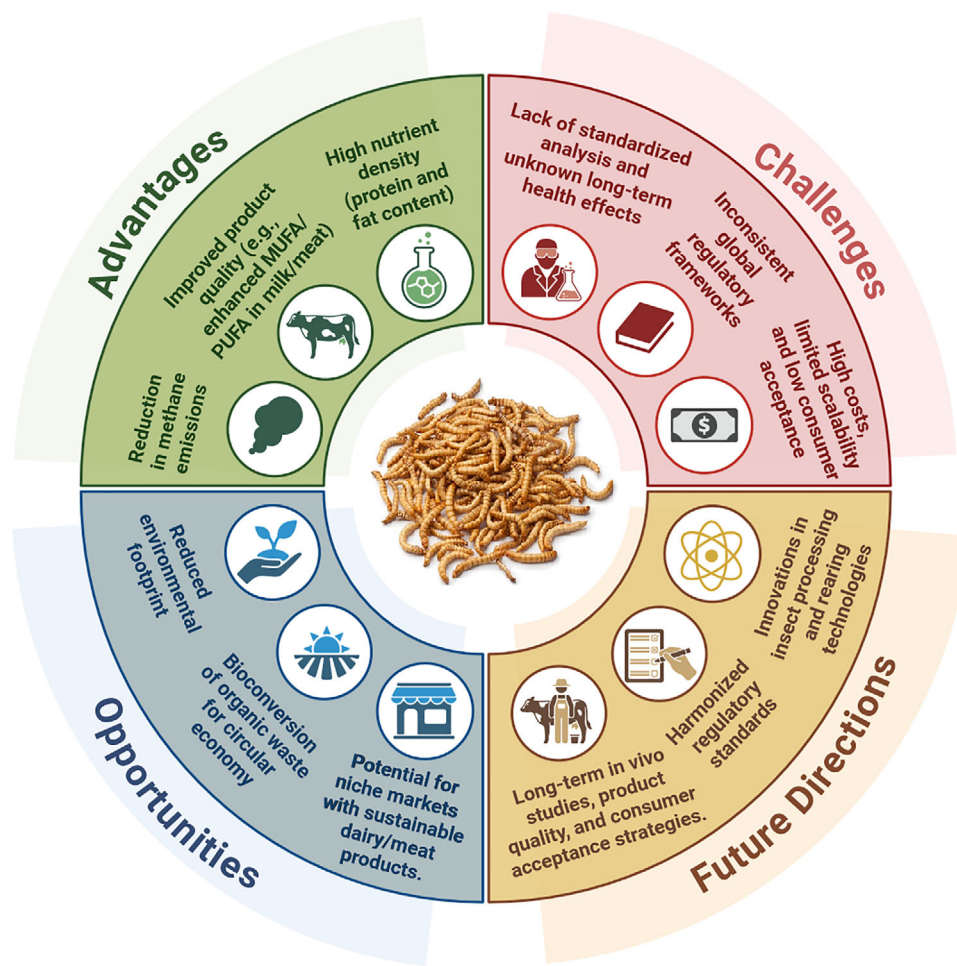


FIGURE 6 | Are insects a sustainable solution for ruminant nutrition? (created in BioRender).

of insect-based diets on ruminant health, reproduction, and product quality, particularly for neonatal calves with underdeveloped rumens. Optimised feed formulations should be developed to balance insect meals with other ingredients, maximising nutrient bioavailability while minimising antinutritional factors. Comparative analyses of insect species, processing methods (e.g., fresh, dried or defatted), and inclusion levels are essential to establish clear guidelines for different ruminants. Environmental sustainability assessments should quantify greenhouse gas emissions, water usage, and land use impacts of scaled-up insect farming, with a focus on integrating circular economy principles through organic waste utilisation. Additionally, consumer perception studies and targeted communication strategies are crucial to enhance market acceptance, emphasising the sustainability and nutritional benefits of insect-fed ruminant products. Collaboration with policymakers is imperative to develop evidence-based regulations that ensure feed safety and support industry growth.

8 | Conclusion

Insect-based feeds offer a transformative opportunity to enhance the sustainability and resilience of ruminant production systems. Their potential to reduce environmental impacts, improve feed efficiency, and support circular economy principles aligns with

global sustainability goals. However, addressing critical knowledge gaps in nutrient standardisation, long-term health effects, environmental impacts, consumer acceptance, regulatory frameworks, and production scalability is essential. By prioritising rigorous, multidisciplinary research and fostering collaboration among researchers, policymakers, and industry stakeholders, the dairy and ruminant industries can overcome these challenges and integrate insect-based feeds into sustainable production systems. This approach will not only enhance resilience and efficiency but also pave the way for innovative, environmentally friendly ruminant farming practices.

Author Contributions

Navid Ghavipanje: conceptualisation, validation, data curation, methodology, writing – original draft, writing – review and editing, visualisation and project administration. **Manuel Gonzalez-Ronquillo:** writing – review and editing. **Manuela Renna:** writing – review and editing. **Mohammad Hasan Fathi Nasri:** writing – review and editing. **Agustín Corral-Luna:** writing – review and editing. **Ahmed Eid Kholif:** writing – review and editing. **Marcello Mele:** writing – review and editing. **Einar Vargas-Bello-Pérez:** conceptualisation, validation, writing – review and editing. All the authors approve the final version of the manuscript and agree to be accountable for its contents.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analysed during this study are included in this published article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: vms370988-sup-0001-SuppMat.xlsx