Environment, Development and Sustainability
https://doi.org/10.1007/s10668-024-04874-1

REVIEW

Replacement of soy by mealworms for livestock feed - A comparative review between soy and mealworms considering environmental aspects

Shahida Anusha Siddiqui[1,2] · **Wadah Elsheikh**[3] · **İlknur Ucak**[4] · **Muzaffar Hasan**[5] · **Zerlina Cleantha Perlita**[6] · **Bara Yudhistira**[7]

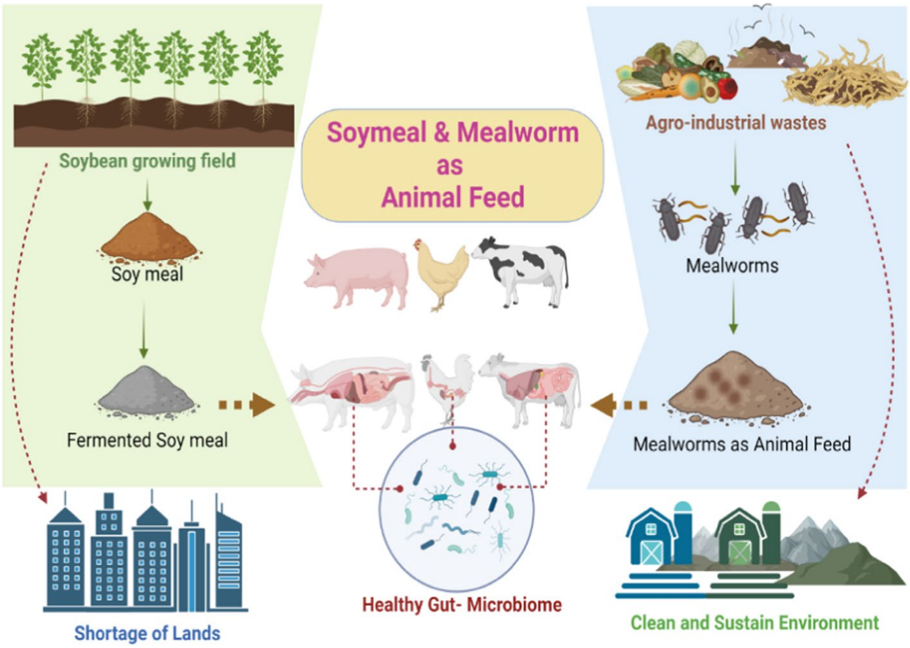
Received: 7 February 2024 / Accepted: 1 April 2024

Abstract

The urgent need for sustainable alternatives to conventional livestock feed has prompted research into novel protein sources. This review paper systematically evaluates the prospect of replacing soy with mealworms in livestock feed, focusing on comprehensive comparisons of nutritional content and environmental considerations. The nutritional profiles of soy and mealworms are analyzed in terms of amino acid composition and digestibility. The total essential amino acids in mealworms are 26.02 g/100 g while in mealworms total EAA is 31.49 g/100 g. The protein content in mealworm is high (51.93 g/100 g) in comparison to soy meal (44.51 g/100 g). Environmental aspects, including deforestation, pesticide use, water consumption, land use, and greenhouse gas emissions, are scrutinized for both soy cultivation and mealworm farming.One kg of mealworm meal yields 141.3 MJ energy use, 3.8 kg CO_2 equivalent for climate change, 25.6 g SO_2 equivalent for acidification, 15.0 g PO_4 equivalent for eutrophication, and 4.1 m^2 land use. It's more potent per kg of protein than soybean or fish meal. Feasibility, scalability, and economic considerations are explored to understand the practical implications for livestock farmers. Consumer perception and regulatory frameworks are also addressed, highlighting potential challenges and strategies for acceptance. The paper concludes by synthesizing key findings and offering recommendations for stakeholders interested in the sustainable integration of mealworms into mainstream livestock agriculture. This comparative review provides a holistic understanding of the potential environmental benefits and challenges associated with replacing soy with mealworms in livestock feed.

Extended author information available on the last page of the article

Graphical abstract



Keywords Livestock meal · Protein · Environment · Soybean · Edible insects

Abbreviations

GHG	Greenhouse gas
LCA	Life cycle assessment
NSP	Non-starch polysaccharides
ANF	Anti-nutritional factors
PUFA	Polyunsaturated fatty acids
MJ	Megajoule
FCR	Feed conversion rate
SBM	Soybean meal
MWL	Mealworms larvae
MWM	Mealworm meal
CP	Crude protein
AA	Amino acid
CFU	Colony forming units
LAB	Lactic acid bacteria
GGT	Gamma glutamyl transferase
Eq	Equivalent
ADG	Average daily gain
ADFI	Average daily feed intake

FBW	Final body weight
WG	Weight gain
BSF	Black soldier fly
DHR	Dried hotel residues
CAGR	Compound annual growth rate
DFW	Dehydrated food wastes
DM	Dry matter
GOT	Glutamic-oxaloacetic transaminase
ANFs	Anti-nutritional factors
IgA	Immunoglobulin A
IgM	Immunoglobulin M

1 Introduction

Sustainable production of healthy food for a growing global population, in the face of the uncertainties of climate change, represents a major challenge for the coming decade. The UN Food and Agricultural Organization (FAO) estimates that the world will have to produce 70% more food by 2050 (Truong et al., 2019). In the face of human population growth, increased longevity, and the uncertainties of climate change, the ability to sustainably produce sufficient food to feed the world is of increasing concern. Concerning animal protein production, the International Feed Industry Federation believes that the production of meat (poultry, swine, and beef) will even double (Veldkamp & Bosch, 2015). Livestock provide food with high nutritional value but are frequently fed on human-edible crops and are associated with significant production of greenhouse gases (GHG). This poses severe challenges to the global capacity to provide enough animal feed. Feed is a key pillar in the journey of improving the productivity of livestock production to increase the contribution of this sub-sector to the overall economic growth. To improve the productivity of livestock under smallholder farmers' conditions, quality feed is the main determinant factor. Currently, important protein ingredients for animal feed are fish meal, processed animal proteins and soybean meal (Sánchez-Muros et al., 2016). Still, feed quality and safety are the big questions even in the commercial feed sector due to the high price of ingredients and compound feeds (Kassymbek et al., 2023). Soybean meal serves as the primary protein source in animal production. Nonetheless, it is hampered by anti-nutritional factors like trypsin inhibitors and antigen proteins, which diminish its nutritional quality and hinder animal production (Yuan et al., 2017). The current production systems for livestock are an unsustainable use of natural resources; animals are often fed on crops that are edible by humans and that require a high proportion of the planet's water resources, as well as producing a significant proportion of global GHG emissions. In recent years, insects have attracted increasing attention as both a human food and an animal feed ingredient. They are frequently considered to be a rich source of essential nutrients that can be grown on low-value feeds and have a low carbon footprint.

Insects are such an alternative animal protein source because they can sustainably be reared on organic side streams and they have a favourable feed conversion efficiency (Veldkamp et al., 2012), likely because they are cold blooded. Insects identified as most promising for industrial production in the Western world are the black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), and yellow mealworm (*Tenebrio molitor*, TM). Recently, there is an interest in the utilisation of insects such as black soldier fly larvae, maggot meal, earthworm and mealworm as potential replacement of soya-bean and fishmeal as protein source in poultry ration (Van Huis et al., 2013; Khan et al., 2016). Even though mealworms have many benefits, it's crucial to remember that the choice of insect for producing feed is dependent on a number of variables, such as the target animals' unique nutritional needs, cost-effectiveness, and geographical availability. Further insights and advances in the use of different insect species for animal feed may also be revealed by continuing study in the field of insect farming. TM, well-known mealworm, represents one of the most interesting edible insects studied as feed and food as it can be easily reared and maintained at early stages and also due to its larval size (Ghaly & Alkoaik, 2009; Morales-Ramos et al., 2012). The edible larvae of the common pest insect TM (yellow meal- worm; YMW) distributed worldwide are a good source of protein, fat, vitamins, and minerals (Kim et al., 2014). YMWs contain high-quality protein (Shockley & Dossey, 2014), and contain more essential amino acids than soybeans (Yi et al., 2013). In addition, they have higher unsaturated fatty acid content than meat, and are relatively rich in vitamin A and iron (Rumpold & Schlüter, 2013). Meal-worms have been grown on dried and cooked waste materials from fruits, vegetables, and cereals in various combinations (Ramos-Elorduy et al., 2002). For future utilization of insects as sustainable animal feed ingredients, it is important to grow them from sources that cannot be included directly in feed for pigs or poultry. Mealworms are the larvae of two species of darkling beetles of the Tenebrionidae family: the yellow mealworm beetle (YMB) (*Tenebrio molitor* L.), and the smaller and less common dark or mini mealworm beetle (*Tenebrio obscurus Fabricius*). Mealworms are easy to breed and feed, and have a valuable protein profile. For these reasons, they are produced industrially as feed for pets and zoo animals, including birds, reptiles, small mammals, batrachians, and fish. They are usually fed live, but they are also sold canned, dried, or in powder form (Veldkamp et al., 2012). Mealworms are useful for their high protein content. They are also used as fishing bait. They are commercially available in bulk and are sold in containers of bran or oatmeal. In 2015, it was discovered that mealworms are capable of degrading polystyrene into usable organic matter at a rate of about 0.35–0.40 mg/day (Finke & Winn, 2004).

Various types of waste generated in the environment are primarily categorized as organic, plastic, agricultural, and industrial waste. Consequently, a range of strategies, including photo catalysis of organic waste, are employed to address waste issues and mitigate associated risks (Zinatloo-Ajabshir et al., 2019). Utilizing green technologies to convert toxic organic waste into valuable salts is one of the most prevalent methods to counter environmental hazards and protect human health (Tabatabaeinejad et al., 2021; Zinatloo-Ajabshir & Salavati-Niasari, 2016; 2019, 2020). Likewise, employing green technologies such as insect rearing shows significant promise in transforming these wastes into high-value products for consumption, benefiting both human health and the environment. The mealworm is very efficient at bio converting organic waste. For this reason, this species is receiving increasing attention, as they could collectively convert 1.3 billion tons of bio-waste per year (Veldkamp et al., 2012). Figure 1 is briefly explaining the mechanism of conversion of agricultural and other wastes into useful by-products through the mealworm.

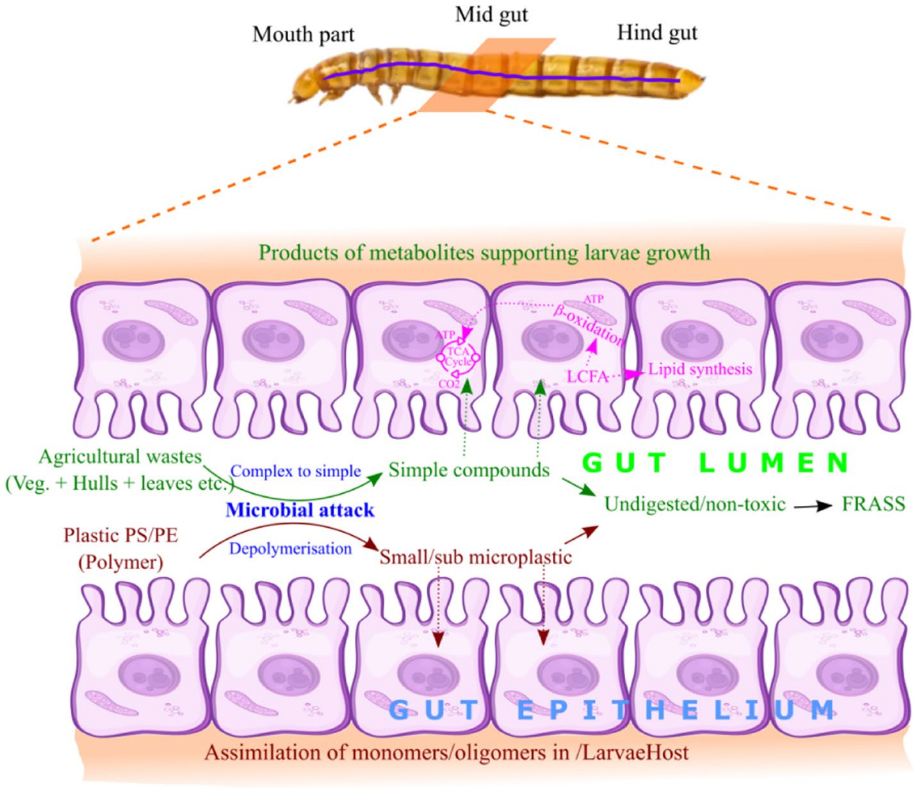


Fig. 1 A concise explanation of the mechanism for converting agricultural and plastic waste using mealworms

2 Different combinations of mealworms and soy in livestock feed for different purposes

2.1 Combination of mealworms and plants

Chokeberry is primarily grown in the eastern and southern regions of Europe as an industrial crop, while it has a historical tradition of medicinal use in North America (Kokotkiewicz et al., 2010; Seidemann, 1993). Chokeberry serves as a key component in the production of juices, wines, jams, and functions as both a coloring agent and a nutritional supplement (Kulling & Rawel, 2008). Chokeberries contain carbohydrate (15%), protein (1%), fat (1%), dietary fiber (7%), and also offer a significant amount of vitamin C. They contain a moderate quantity of vitamin K, and boast a wealth of antioxidants, such as anthocyanins, quercetin, and resveratrol. Nonetheless, the management of chokeberry waste presents a significant environmental challenge. The process of pelleting chokeberry by-product (CBP) meal not only minimizes food waste but also contributes to recycling within the poultry industry, providing a sustainable solution to the problem of chokeberry waste disposal. In this regard, the incorporation of pelleted *Tenebrio molitor* (TM) powder along with CBP meal represents a means to enhance poultry production and meat quality by reducing feed wastage (Jeong 2022) (Fig. 2). Choi (2023) explored the impact of incorporating pelleted TM powder and CBP meal into the diet on the growth characteristics and meat quality of Pekin ducks. Authors found the significant difference in final body weight (FBW), weight gain (WG) and feed conversion ratio (FCR) ($p < 0.05$). Furthermore, the incorporation of up to 3% pelleted TM powder alongside CBP meal in the duck diets enhanced growth production and antioxidant attributes in the quality of duck meat. The authors suggested that the improved growth performance and meat quality might be attributed to the effects of pelleting, which results in higher digestibility and a well-balanced nutrient supply (Abdollahi et al., 2019), as well as the interaction of bioactive compounds, such as the phenolic constituents found in TM powder and CBP meal (Kulling & Rawel, 2008).

Park et al. (2023), investigated the effect of feeding combination diet to mealworm protein hydrolysate (MWPH) and cranberry fruit extract (CFE) on mouse growth. The authors noted that adding MWPH and CFE to the regimen enhanced their anti-inflammatory effects through the regulation of cytokine activation, lowered the expression of IL-1, improved immune function, reduced the population of harmful gut bacteria, and increased the levels of antioxidant enzymes in the serum.

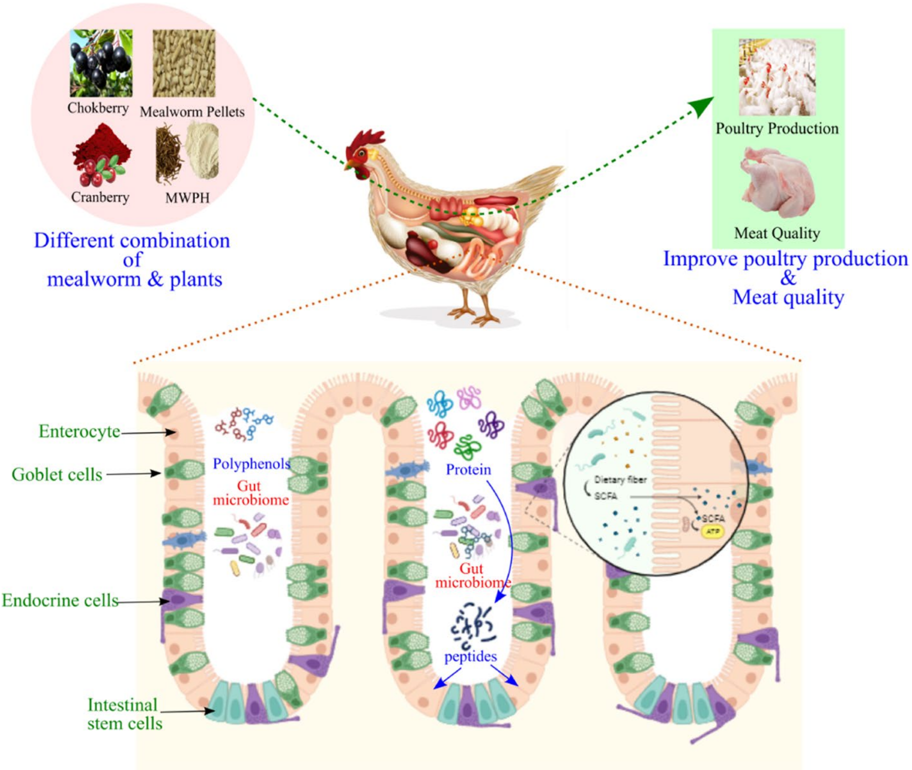


Fig. 2 Illustrating the integration of mealworms and plant waste in enhancing both poultry production and meat quality

2.2 Combination of soy and alga or bacteria (fermented soy feed)

In a study conducted by Wang et al., 2018), the impact of supplementing sow diets with fermented mixed feed (FMF) during lactation on the performance of both sows and their offspring was examined. The authors observed that co-fermentation of corn and soybean meal (SBM) mixed feed with *Bacillus subtilis* ZJU12 and *Enterococcus faecium* had a positive impact on nutrient availability and utilization. This treatment also led to improvements in milk yield and milk IgA content. The authors proposed that during co-fermentation, *Bacillus subtilis* ZJU12 effectively reduced trypsin inhibitor and other anti-nutritional factors (ANFs), while increasing the crude protein and small peptide content (Seo & Cho, 2016). Furthermore, the FMF provided sows with a rich source of live *Bacillus subtilis* ZJU12 and *Enterococcus faecium* cells, along with their metabolites, including lactic acid and enzymes.

Yuan et al., (2017) substitute the plasma protein (PP) and soybean protein concentrate (SBPC) with fermented soybean meal (FSBM) in swine feed. The authors administered the piglets with fermented SBM and studied the effect of fermented SBM on piglet performance. The SBM was co-fermented with *Bacillus subtilis, Hansenula anomala* and *Lactobacillus casei* in 2:1:2 ratios. The results showed that 10% fermented SBM improved average daily gain (ADG), and feed conversion ratio (FCR). The substitution with fermented SBM in piglet diet had improved nutrient digestibility and also improved gut microflora (Fig. 3). Reports indicate that utilizing FSBM in piglet diets

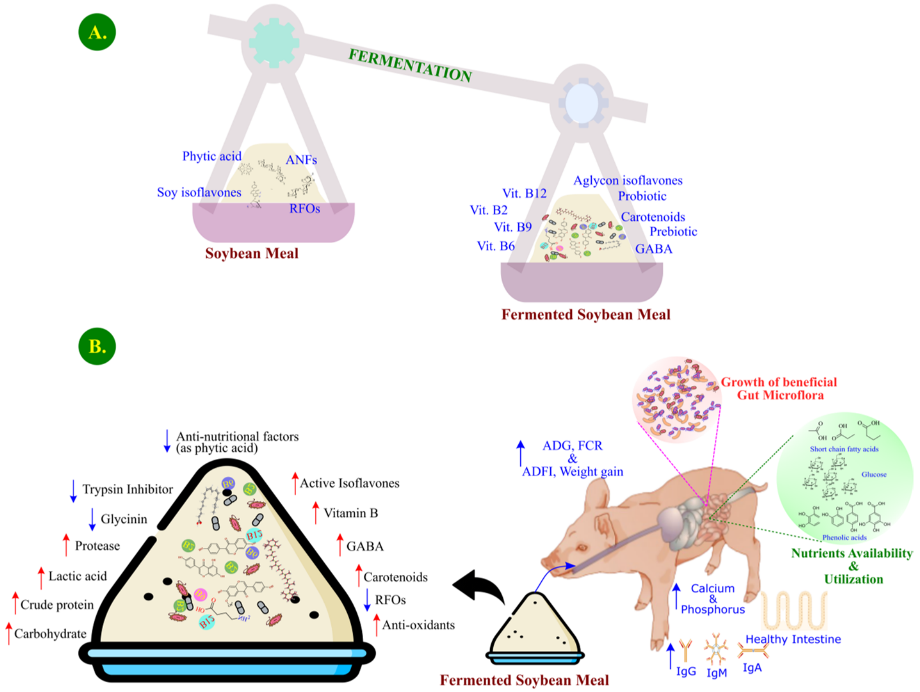


Fig. 3 Fermented soybean meal (FSBM) for animal feed. **a** The role of fermentation in SBM conversion into nutritious and functional SBM, **b** the advantageous outcomes of consuming FSBM

with *Bacillus subtilis* can serve as a highly digestible protein source (Nam et al., 2012). This is attributed to the significant protein hydrolysis into amino acids and peptides. Furthermore, the inclusion of *Lactobacillus* enhances intestinal function, fosters nutrient digestion and absorption, and regulates immune function (Vanbelle et al., 1990; Yuan et al., 2017). This study demonstrated that fermenting SBM with the ideal microbial blend could substantially reduce trypsin inhibitor and antigen protein levels while increasing soybean peptide content six-fold. These results surpass those obtained from single microbial fermentation, as reported previously (Hachmeister & Fung, 1993; Mital & Garg, 1990).

Similarly Feng et al., (2007) feed the broiler chicks with *Aspergillus oryzae* fermented SBM and observed that FSBM supplemented broilers achieved high ADG and ADFI ($P<0.05$) in comparison to SBM feeded. FSBM also enhanced the level of phosphorus and IgM in the serum. Fermentation changed the physical and nutritional characteristics of soybean meal. Several studies have been reported that after fermentation of SBM crude protein, dry matter, crude fat increased, and carbohydrate content decreased. In addition, various reported showed that fermented SBM improved weight gain; feed efficiency, phosphorus bioavailability in broiler chicks (Chah et al., 1975; Hirabayashi et al., 1998; Zamora & Veum, 1979) and similarly in pigs (Kiers et al., 2003). Chah et al. (1975) suggested that the enhanced growth-promoting effects of fermented soybeans primarily resulted from an increased provision of essential amino acids and potentially vitamins synthesized by the fungi. Fermented soy-based products offer high digestibility and nutritional value, providing essential nutrients such as calcium, as well as Vitamins A and B, while also possessing functional properties. In addition, employing *Aspergillus oryzae* in the fermentation process can enhance the nutritional quality of soybeans and soybean meal. This underscores the potential of utilizing FSBM with reduced trypsin inhibitor levels and an increased concentration of small-size peptides as a promising alternative to animal-derived protein ingredients in young animal diets (Hong et al. (2004).

The presence of anti-nutritional factors (ANFs) in SBM significantly impacts both oxidative balance and immune responses in fish. The *Aspergillus awamori* fermented SBM significantly reduced the contents of ANFs in SBM, including raffinose (−98.8%), stachyose (−80%), trypsin inhibitors (−80%), glycinin (−98.5%), and β-conglycinin (−97.4%). The FSBM also enhanced the height of enterocyte and microvilli in turbot fish (*Scophthalmus maximus* L.) (Li et al., 2019). Wu et al. (2020), used high temperature *Bacillus stearothermophillus* FSBM and antibiotic growth promoters (AGP) free feed as dietary supplements to broiler chicks to investigate the effect on growth performance. Authors found that the aforementioned dietary supplement improved the intestinal gut microflora, increased the weight of thymus and bursa of Fabricius, and also enhanced glutamic-oxaloacetic transaminase (GOT) level in serum. Similarly, *Lactobacillus plantarum* FSBM was used as dietary supplement for turkey which improved the histology of the small intestine and stimulated the antioxidant and immune system (Chachaj et al., 2019a, 2019b). Histomorphological examinations had revealed that substituting a portion of soybean meal with fermented soybean meal in turkey diets led to an elevation in villus height and the villus height/crypt depth ratio. Furthermore, it's noteworthy that the fermentation of soybean meal notably reduces the levels of allergenic proteins such as glycinin and β-conglycinin. The enhanced morphological characteristics of the intestine facilitated increased nutrient absorption and led to higher body weight gains in the birds, along with an improved feed conversion ratio (FCR) (Chachaj et al., 2019a, 2019b). In their study, Cheng et al., (2019) examined the optimal conditions for the mixed solid-state fermentation (SSF) of soybean meal using protease and probiotics, and assessed the impact of FSBM on broilers.

The authors observed that 10% FSBM showed high ADFI and also inhibited the allergic immune response in broilers.

2.3 Combination of soy and food waste

2.3.1 Food wastes

The primary concern when it comes to feeding food waste to broilers is the high ligno-cellulosic content (King et al., 2013). Some research suggests that methods for breaking down the abundant cellulose content in plants could be practical for numerous small-scale farmers worldwide. For instance, a well-established approach like ensiling only necessitates specific bacteria (lactic acid bacteria) to digest cellulose and hemicellulose over time (King et al., 2013). Processing food waste for use in poultry feed is alsocrucial because moldy feed not only diminishes its nutrient composition but also posesrisks to animal health. Consequently, drying or fermenting food waste is a practice that can inhibit mold growth and should be considered when incorporating food waste into poultry feed. When it comes to preserving food, drying requires about 250–300 L of fuel and 200 kWh of electricity for every ton of dehydrated product (with 88–90% dry matter) (Chedly & Lee, 2000). In contrast, ensiling preserves food while retaining many of its nutrients. Numerous studies have consistently demonstrated that broilers fed varying percentages of food waste perform similarly to those on a standard diet of corn and soy (see Table 1; Damron et al., 1965; Al-Tulaihan et al., 2004; Joshi et al., 2000; Wadhwa & Bakshi, 2013; Stefanello et al., 2016). Table 1 explains in general that different waste materials from various stages of the food supply chain. For example, dried, ground carrot and oyster mushroom waste originate from the harvesting sector, while dried tomato pomace, carrot top hay, cornflakes waste, and meat meal are sourced from the manufacturing/processing sector.

2.3.2 Bakery wastes

Bakery waste has been effectively incorporated into broiler feed in previous studies (Al-Tulaihan et al., 2004; Damron et al., 1965; Stefanello et al., 2016). Damron et al. (1965) observed that including up to 10% dried bakery product in the diet did not result in significant differences in body weights or feed conversion ratios compared to 56-day-old broilers exclusively fed corn/soy diets. Similarly, Al-Tulaihan et al. (2004) noted that adding up to 30% dried bakery waste to the diet did not lead to significant differences in body weight, feed conversion ratio, or feed intake when compared to 42-day-old broilers fed exclusively corn/soy diets. Furthermore, Navidshad and Seifdavati (2009) found that providing broilers with meal at levels of 65 and 80 g/kg feed in a corn/soy-based diet resulted in comparable daily weight gain, daily feed intake, and feed conversion ratios to birds fed a full corn/soy diet. Additionally, studies using waste from fermented fish, various fruits and vegetables, fermented apple pomace, and dried leftover Korean food have also supported their inclusion in broiler diets (Bakshi et al., 2016; Hammoumi et al., 1998; Joshi et al., 2000; Wadhwa & Bakshi, 2013).

2.3.3 Hotels/restaurants wastes

Restaurant food waste often has a moisture content ranging from 50 to 85%. When considered on a dry matter (DM) basis, these wastes are rich in nutrients suitable for pig feed. Typical

Table 1 Various combinations of mealworms and soybean meal are utilized in livestock feed for various specific purposes

Diet/supplement	Animal	Remarks	References
TM powder + CBP	Duck	Improved FBW, WG, FCR Improved meat quality Enhanced antioxidant activity	Choi, (2023)
MWPH + CFE	Mice	Improved body weight Improved anti-inflammatory activity Reduced number of harmful gut microbiome Enhanced antioxidant activity enzyme	Park et al., (2023)
Fermented soy feed			
Fermented (*Bacillus subtilis* ZJU12 and *Enterococcus faecium*) Corn and SBM	Sows	Improved nutrient availability and utilization Improved milk yield and IgA content	Wang et al., (2018)
Bacillus subtilis, *Hansenula anomala* and *Lactobacillus casei* Co-Fermented SBM	Female Pigs	Improved nutrient digestibility Enhanced enzyme activity Increased LAB counts Reduced *E.coli* counts	Yuan et al., (2017)
Aspergillus oryzae Fermented SBM	Broilers chicks	Improved ADG and ADFI Improved P content and IgM in serum	Feng et al., (2007)
Aspergillus awamori Fermented SBM	Turbot (Fish)	Reduced ANFs Improved the height of enterocyte and microvilli	Li et al., (2019)
High temperature *Bacillus stearothermophillus* fermented SBM	Broiler chicks	Increased weight of thymus and bursa of Fabricius Reduced GOT level in serum Improved the intestinal morphology and gut microflora	Wu et al., (2020)
Lactobacillus plantarum fermented SBM	Turkeys	Improved intestinal histology Stimulate the antioxidant and immune system	Chachaj et al., (2019a, 2019b)
Protease with *Bacillus subtilis* fermented SBM	Broiler chicks	Reduced ANFs	Cheng et al., (2019)
0*Combination of soy and food wastes*			
Dried hotel residue	Male pigs	Not affect meat quality and feed utilization	Giamouri et al., (2022)
Dehydrated restaurant food waste	Pigs	Unchanged ADG Softer carcass fat	Myer et al., (1999)
Fresh food wastes (Fish and fruits)	Pigs	No effect on ADFI, ADG Lower backfat thickness	Márquez & Ramos, (2007)

Table 1 (continued)

Diet/supplement	Animal	Remarks	References
Vicia faba L. var. minor	Poultry		Pirgozliev et al., (2023)
faba beans (18%) or peas (20%)	Pigs	No change in productive performances, expressed as body weight and FCR	Gatta et al., (2013)
toasted fava beans	Holstein cows	Increased lactose concentration and decrease protein in milk	Hansen et al., (2021)

analyses (DM basis) show crude protein (CP) contents between 15 and 23%, fat content ranging from 17 to 24%, and ash content measuring from 3 to 6% (Truong et al., 2019). The practice of using food waste as pig feed is not a novel concept. However, due to health and safety considerations, several states have prohibited the direct feeding of food waste to pigs. In states where it is permitted, regulations necessitate the cooking of food waste before it is fed to pigs. The increased oversight, associated costs, labor-intensive processes, relatively modest pig performance, and concerns about meat quality have diminished interest in the traditional approach of feeding food waste or garbage to pigs (Suwarno et al., 2023). Nonetheless, as waste disposal methods become costlier and landfill space grows scarce, recycling food waste for livestock feeding has emerged as an appealing waste management alternative. Modern technology now enables the conversion of food waste into dry, stable products that can be seamlessly integrated into contemporary pig feeding programs.

In 2019 study, Truong et al., reported that pigs efficiently utilized dehydrated food waste (DFW) products, including the higher fat content present in the DFW diets. Their findings suggest that dehydrating restaurant food waste holds promise as a means of creating a nutritious feed ingredient for swine diets, all the while offering an effective solution for solid waste management. Similarly, dietary inclusion of dried hotel residues (DHR) has minimal impact on pig growth performance, with no significant differences in feed conversion ratio, dressing percentage, or meat quality traits when compared to a commercial finisher diet without food waste. The inclusion level of food waste was carefully chosen to prevent a substantial increase in dietary ether extract content (Giamouri et al., 2022). These findings endorse the use of dried food residues in pig feeding, provided safety and quality standards are upheld. Further research is needed to optimize the transformation of food waste into animal feed, ensuring sustainability and cost-effectiveness in pig farming.

2.4 Combination of soy and other plants

Gatta et al. (2013) examined the partial replacement of soybean meal with faba beans (18%) or peas (20%) in pig diets. The study found that the productive performances, including body weight, feed conversion ratio, and meat quality attributes, were similar between pigs fed faba bean or pea diets and those fed solely soybean meal. Interestingly, the substitution with faba beans seemed more favorable than with peas, notably due to higher polyphenol content in the diet and elevated levels of phytoestrogens in the animals' plasma and muscle. Additionally, pyrimidine anti-nutritional compounds in the diet did not accumulate and had no impact on animal growth performance.

Hansen et al., (2021), studied the impact of replacing mixtures of wheat and soybean meal, as well as wheat and rapeseed meal, with toasted fava beans in Holstein cows' diets. They discovered that toasted fava beans can effectively replace these mixtures while maintaining equivalent milk production. However, when toasted fava beans were used as substitutes for soybean meal and wheat or rapeseed meal and wheat, there was a reduction in milk protein yield (Kairiša et al., 2023).

3 Companies involved in mealworms and soy feed production

The mealworms market is projected to achieve a value of $1.27 billion by 2030, with a compound annual growth rate (CAGR) of 25.8% between 2022 and 2030. In terms of volume, the market is anticipated to expand at a CAGR of 28.6% during the same period, reaching 367,491.7 tons by 2030. Market growth is fueled by several factors, including rising GHG emissions from livestock and poultry industries, the high nutritional value of mealworms, environmental advantages of consuming edible mealworms, and a lower risk of zoonotic diseases compared to animal-derived products. However, potential allergic reactions to mealworm consumption are expected to somewhat hinder market growth. Prominent players in the mealworms market (Table 2) include Protix B.V. (Netherlands), Ÿnsect SAS (France), BETA HATCH (U.S.), Armstrong Crickets Georgia (U.S.), TEBRIO (formerly MealFood Europe SL) (Spain), Tebrito AB (Sweden), Entec Nutrition (U.K.), Invertapro AS (Norway), Keil Co., Ltd (South Korea), EntoBreed Farming BV (Netherlands), and Goterra (Australia). In 2022, the animal nutrition sector is expected to hold the most significant share of the mealworms market based on end use. This growth is attributed to factors like the rising animal population, increased spending on pets, greater consumer willingness to offer premium pet food, the cost-effectiveness of insect-based feed versus other animal feed types, and the growing demand for insect protein within the pet food industry.

Numerous companies in the United States, such as Beta Hatch Company, employ IoT-enabled flagship facilities for automated climate control to ensure optimal conditions for insect growth. Utilizing waste heat from a nearby data center—dedicated to generating vast amounts of information on protein production efficiency—these companies leverage robotics and automation to scale up insect production for industrial purposes. The incorporation of custom sensor arrays enables high-density condition sensing, facilitating big data learning for production optimization. In addition to employing big data genome analytics, these companies are actively exploring RNAi and CRISPR/Cas9 as tools to tailor their insects according to specific requirements. Presently, traditional breeding methods are informed by advanced tools, but the future holds the promise of enhancing methionine content, accelerating metabolism, and delivering vaccines and custom proteins to animals through feed (https://betahatch.com/products/).

To cultivate mealworms, Tebrio Company partners with SCA, a Swedish timber, paper, and pulp manufacturer. SCA generates biosludge as a byproduct of paper production, typically considered waste with no inherent value, requiring disposal. However, when insects, such as mealworms, consume this biosludge, it transforms into fish feed. The byproduct of the larvae production, serving as either fertilizer or fish feed, returns to SCA. SCA, in turn, utilizes this material to plant its forest seedlings, creating a sustainable and circular process (https://tebrio.com/en/animal-food/#).

4 Nutritional value of mealworms and soy feed

Since a growing population increases demand for food and other resources, particularly animal protein, the livestock business is essential to agricultural food production. The two most significant sources of protein used in animal production are soy and fishmeal (Godde et al., 2021); where they are commonly utilized because of their high protein content and digestibility. Monogastric animals eat mostly soybeans as their main source of protein, yet certain species cannot consume soybeans because of their anti-nutritional components. Studies have shown that soy-based diets prevent the growth of monogastric animals, mainly because they make the digest more viscous and hence restrict nutrient absorption. Protease inhibitors and lectins are a few of the anti-nutritional elements present in soybean

Table 2 Gist of countries vise companies involved in mealworm and soy feed production

Company	Country site	Product	Brand	References
Ynsect SAS	France	Hydrolysate15 Mealworms		https://www.ynsect.com/chickens-pigs/
Protix B.V	Netherlands	ProteinX LipidX PureeX Flytilizer BSF eggs OERei		https://protix.eu/products_by_protix/
Beta Hatch	U.S	Mealworm meal Mealworm oil Whole dried mealworm		https://betahatch.com/products/
Armstrong Crickets Georgia farm	U.S	Superworm, mealworm, giantworm, hornworm, wax worm, and crickets		https://www.armstrongcricket.com/
Tebrio	Spain	Protein/Lipids/Meal		https://tebrio.com/en/animal-food/#
Keil Co., Ltd	South Korea	Formulation and packing machine		https://en.keilcorp.com/75
Tebrito AB	Sweden	Mealworm, Frass		https://www.tebrito.se/
Invertapro AS	Norway	Mealybug larvae	URFOR	https://www.invertapro.com/
Entec Nutrition	U.K	Mealworm		https://www.entecnutrition.com
EntoBreed Farming BV	U.K	Mealworm		https://www.entobreed.com/en/entobreed/
Grand Master	Kerala, India	Soya Meal Cattle Feed	Grand Master	https://www.grandmasterglobal.com/soya-meal-animal-feed.php
Megataj Agrovet PVT. Ltd	Nagpur, India	Soybean meal	Sea Gold	https://animalsfeed.com/
Sonic Biochem	India	De oiled soy hipro flour and flakes (toasted and untoasted)		https://www.sonicbiochem.co.in/products-and-applications/
Goterra	Australia	Mealworm protein BSF protein Frass		https://goterra.au/insect-protein-products/

grains. One of the main contributors to the anti-nutritional effects of soybeans is their presence of thermo-stable anti-nutritional components, which include non-starch polysaccharides (NSP) and oligosaccharides. The insoluble NSP is made up of cellulose polymers and certain hemicelluloses. Monogastric animals rely on bacterial fermentation for digestion because they lack the enzymes needed to hydrolyze these sugars (Bueno et al., 2018). The major category of anti-nutritional factors (ANF) found in raw beans is trypsin inhibitors. Heat inactivates this ANF, allowing higher quantities of soy beans to be used in animal feed. Heat, on the other hand, enhances the occurrence of Maillard reactions, lowering the digestibility of the soy bean (Ibáñez et al., 2020). Pigs have a limited ability to digest phytic acid, which is associated with phosphorus in soy products (Degola et al., 2019).

Many studies have linked economically important features of soybean production, including productivity and oil or protein content (Bueno et al., 2018). Generally, soybean seeds contain 5.6 to 11.5% water, 32 to 43.6% crude protein, 15.5 to 24.7% fat, 4.5 to 6.4% crude ash, 10.9 to 14.9% neutral detergent fiber, 9.1 to 11.1% acid detergent fiber, and 31.7 to 31.8 percent carbohydrates on a dry matter basis (Banaszkiewicz, 2011). The protein and fat content of soybeans is high. Soybeans are used as a source of protein and fat all over the world in feed. Soybean offers the highest level of crude protein and the ideal balance of amino acids of any legume seed. Comparatively to other vegetable meals with high protein contents, the raw fiber content (approximately 6%) is lower in soybeans. Due to this, they are employed in the process of making soybean oil, which is then utilized to make a very desirable animal feed. Soybeans have a good amino acid profile in addition to being abundant in protein. Soybean protein contains enough amino acids to supplement grain protein and satisfy the demands of animals. However, tryptophan and sulfuric amino acids are unsatisfactory in soybeans. Soybean protein has the highest level of lysine and methionine digestibility (Degola et al., 2019). Soybean oil is frequently used as a feed-grade fat in broiler chicken rations to increase the energy density of feeds and increase feed utilization efficiency (Saleh et al., 2021). This is due to the need to create high-energy diets for modern breeds, as well as the oil's high digestibility and metabolisable energy content. Several variables, including climate changes, genetics, terrain, and soil quality, impact the chemical makeup of soybeans, particularly the content of amino acids (Degola et al., 2019). The amount of fat in soybeans is another crucial quantitative aspect of nutrition. Soybeans fat composition that is approximately 10%–15% saturated fatty acids, 19–41% monounsaturated fatty acids, and 46%–62% polyunsaturated fatty acids (PUFA). Soybean oil has a high energy value. About 99% of the triglycerides in the lipid fraction of soybean seeds are polyunsaturated fatty acids (linoleic and linolenic) and unsaturated oleic acid, both of which are abundant in the lipid fraction (Messina, 2016). The quality of soybean oil is determined by the fatty acid makeup. Because oleic, linoleic, and linoleic acids, among other unsaturated fatty acids, are abundant in soy bean oil, it has a high nutritional value. The high PUFA content of soybean oil has been connected to linoleic acid's function in reproduction and appears to have an energy-independent effect on enhancing reproductive health in dairy cattle. A significant food and feed ingredient is soybeans. Only marginally did nitrogen fertilizer affect the fatty acid makeup of the different soybean types. The soybean is a good source of several vitamins and minerals, particularly potassium (Messina, 2016).

The seed type, environmental circumstances during bean growth, harvest, and storage, as well as the method used to extract the oil, all has an impact on the chemical composition, protein quality, and nutritional value of commercial soy beans (Ibáñez et al., 2020). According to Szostak et al., the genetic characteristics of the variety as well as agro-technical elements, particularly nitrogen fertilization, affect the protein content of legumes.

Furthermore, genetic differences in Glycine soybean biotypes have been found, suggesting that their chemical contents may differ. Soybean products in non-ruminant diets can provide acceptable performance only if diets are properly prepared or anti-nutritive elements are eliminated. Nutrient content, bioavailability, and anti-nutritive characteristics, as well as their impact on the performance of animals, when soybean proteins are exposed to various processing steps, their quality increases (Dei, 2011; Ibáñez et al., 2020).The methods involved either minimizing or removing the ANFs in the beans, significantly improving the dietary value of all animal species. The phases of the processing can have an impact on the protein's quality, depending on the circumstances. The heat used in processing has been found to be the single most critical element influencing quality of the protein in soybean meal. Proteins and amino acids are negatively impacted by high processing temperatures for oilseeds because denaturation or the production of Maillard reaction products occurs (Dei, 2011). Soybean agriculture alone consumes the majority of the area required for animal product production (Stein et al., 2013). The soluble carbohydrates in defatted flakes are taken out to produce soy protein concentrate. Either ethanol extraction or enzymatic degradation can be used to achieve this. Soybean protein concentrate is helpful as a starter feed for piglets and as a milk replacement feed for calves. This is because it only has a very little amount of antigenic substances and heat-stable oligosaccharides. It may replace dried skim milk, whey powder, and fishmeal in pig starter feed, and it has virtually replaced dry skim milk in milk replacer feed (Degola et al., 2019; Dei, 2011).

There was a need to look for alternatives since soybean meal is expensive and because agricultural projects and their production are influenced by the climatic and financial conditions of the nations that produce soybeans. This suggests that there is a pressing need to identify fresh, affordable protein sources for animal production that can provide the same nutrients as soybean and fish meal. One source that might be exploited is insects. Insects provide a viable protein alternative that is suitable for use in both food and feed due to their high protein content. Insects are particularly intriguing for the production of food and feed because of their nutrient makeup and simplicity of upbringing. For instance, the yellow mealworm, *Tenebrio molitor* L., has the potential to take the place of frequently used protein sources in livestock diets. Mealworms are easy to grow and don't need a lot of room for production (Selaledi et al., 2020). Such rising demand for livestock products can be met by identifying and utilizing alternative animal feeding options, which will be critical in developing the animal production sector (Pinotti et al., 2021). Various insect species have been recognized as possible alternatives and more sustainable feed components for cattle in recent years due to their capacity to transform by-products into products rich in protein and other vital nutrients (Adhikari et al., 2021).

Insects are extensively used as food and feed throughout Asia, Africa, and the Americas, while entomophagy is uncommon in Europe. On the other hand, during the past ten years, the use of insects as food and feed has increased. There has been a lot of interest in insects as a food source ever since 2015, when they were recognized as such in the European Union. One of the insects that are most often produced in Europe for feed and food is the yellow mealworm (Bordiean et al., 2020). Mealworms are a great alternative to conventional livestock feed because of their identical essential amino acid content and nutritional profile to that of fish and soybean meal. According to various researches on the diets of hens, the whole or partial substitution of fish or soybean meal with mealworms led to equivalent or even slightly improved growth performance and digestibility (Toviho & Bársony, 2022). According to several studies, it was discovered that adding 10% dry mealworms to dry matter at the beginning of the broiler diet had no negative effects on feed intake, body weight gain, or feed efficiency. Mealworms are very palatable and can take the place of base feed, especially fish meal and soybean meal, according to several studies. The egg ratio produced by the usage of dry mealworms was 2.4%, which was higher than that of other basal diets (Makkar et al., 2014). Numerous insect meals have been investigated as possible alternatives to fishmeal in animal diets. As compared to insect-free diets, dietary insect meals significantly affected growth performance, digestibility, and meat quality, notably the fatty acid profile of fed fish (Gasco et al., 2019). Yellow mealworm has been stated to be one of the most recognized insects as a viable substitute protein due to its availability and low cost (Tran et al., 2021). Protein, lipid, and nitrogen-free extracts of yellow mealworm have been shown to contain between 47.2% and 66.3%, 14.9% to 43.1%, and 2.8% to 3.4%, respectively. In order to show the link between keywords when creating a bibliometric map of the mealworm for the years 2013–2023, Pubmed was used to collate the data (Fig. 4). Where the large circles in the figure represent the terms that the authors most frequently employ, including "*Tenebrio molitor*," "animal," "animal nutrition," and "yellow mealworm”. Based on this bibliometric mapping, we could categorize the terms into five distinct sets. Animal, feed, *Tenebrio molitor*, and nutrient value were among the keywords in the first group (red). Chicken, diet, insect meal, and growth performance make up some of group 2’s (green) components. Insect proteins, biomass, and entomology make up certain parts of Group 3 (blue). Yellow mealworm, larvae, and dietary protein made up group 4 (yellow). Mealworms, poultry, and animal nutritional physiology made up several of Group 5 (purple). Furthermore, the yellow mealworm is rich in vitamins, minerals, and other biologically beneficial substances (Nowak et al., 2016). Depending on the environment’s temperature, photoperiod, relative humidity, and other factors, yellow mealworms have a life cycle that lasts between 280 and 630 days (Makkar et al., 2014). Insects may transform organic byproducts, resulting in economic gains by lowering trash generation and environmental contamination. Insects can use waste as a safe feedstock and

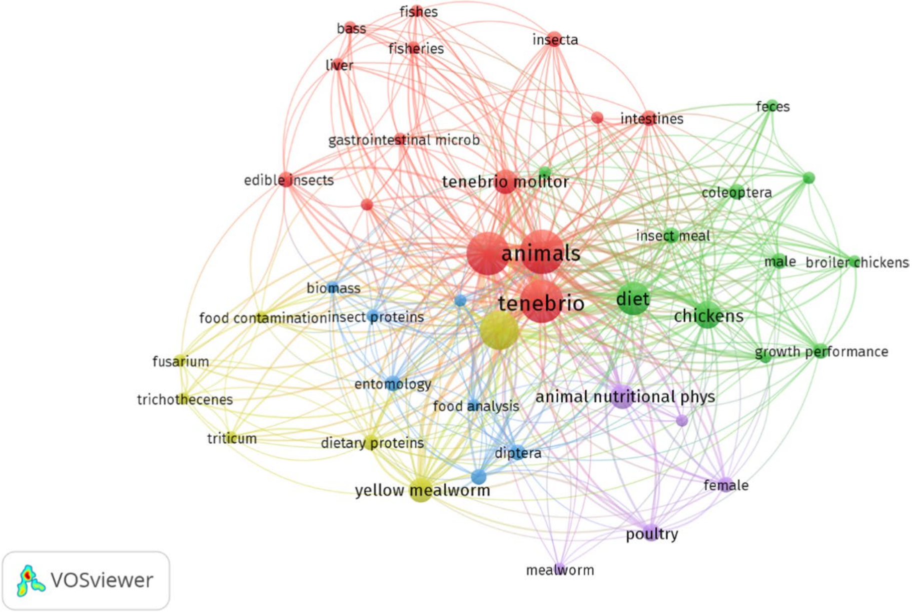


Fig. 4 A bibliometric map of mealworms in animal feed

bio-convert it into high-quality goods with little help from other resources (Bordiean et al., 2020; Makkar et al., 2014). Yellow mealworm can successfully replace fish or soymeal in livestock or fisheries. Plant protein digestion can be difficult for carnivorous fish species; however, mealworm larval meal and oil can be an efficient and nutrient-dense dietary resource. Mealworms can also be fed to chickens and other domestic birds to enhance their diets (Grau et al., 2017). The chemical composition of mealworms is high in crude protein (47–60%) and lipid (31–43%). Fresh larvae have a water content of about 60%. They have a low ash content (5% dry matter) and, like other insects, a very low Ca: P ratio. It should be noted that diet has an influence on the composition, which is highly variable. The amount of essential amino acids in the meal is sufficient. Mealworm food has certain fatty acid compositions with housefly maggot meal and house cricket meal. In comparison to black army fly larvae, mealworm larvae had much higher levels of linoleic acid and significantly lower levels of lauric acid, respectively (Makkar et al., 2014). In general, insects contain less methionine and cysteine and more lysine and threonine, two amino acids that are insufficient in the four most often consumed cereals: wheat, rice, cassava, and maize. Mealworm larvae are also low in calcium but rich in phosphorus; nevertheless, when compared to larvae and beetles, the excreta and exuvium components had the highest calcium concentration (Ravzanaadii et al., 2012). A calcium deficiency and symptoms of metabolic bone disease can occur from feeding mealworms solely to chickens. As a result, calcium supplementation for mealworms is suggested (Selaledi et al., 2020). Table 3 lists a few of the negative and positive effects of mealworms related to their nutritional value in animal nutrition. Compared to more common protein sources like soy bean meal, mealworm manufacturing may be less expensive. Additionally, mealworms improve the growth performance and feed utilization efficiency of poultry diets (Hussain et al., 2017). Economic production parameters for mealworms include requiring less space, having commercial production capabilities, having high conversion efficiency, and utilising organic waste as a food source in a relative sense (Selaledi et al., 2020). Mealworms have higher protein content (51.93%) than soy beans (44.51%), per Bovera et al. (2015). In comparison to maggots and silkworms, mealworms are the best insect meal substitute, according to Khan et al. (2017); they improve broiler performance and meat quality. The concentration of components increases as mealworms go through their metamorphosis (Simon et al., 2013). Comparing mealworms to maggots and silkworms, Khan et al. (2017) found that mealworms are the best insect meal substitute because they improve broiler performance and meat quality. The concentration of essential minerals, including calcium, phosphorus, and zinc, is critical during the transformation stages of mealworms (Simon et al., 2013). Table 4 shows a comparison of the nutritional composition of mealworm and soymeal.

Insects can significantly aid in the sustainable recycling of low-grade bio resources, such as agricultural byproducts (Adhikari et al., 2021). Because the nutritional profiles of mealworm pupae and larvae are comparable, larvae may not always benefit more from the pupal stage in terms of nutrient content and nutrient utilization. Mealworm adults may be a significant source of bioactive substances that have positive effects on the immune system and animal health (Khanal et al., 2023). Previous studies also highlighted that the mealworm larvae may be grown to an appropriate size using agricultural by-products, including resources derived from wheat (Zhang et al., 2019). Mealworms may be used as a substitute feed for monogastric and ruminant animals, according to Khanal et al. (2023). Khanal et al. (2023) imply that larvae and pupae usually had a similar nutritional profile, with crude fiber, crude protein, and total amino acid contents that were lower and crude fat, total fatty acid, and gross energy levels that were greater in comparison to adults. Overall essential and non-essential amino acid concentrations in larvae and pupae were comparable to those

Table 3 The negative and positive effects of mealworms in animal feeding

Advantages	Disadvantages	References
A greater immunological response and improved disease resistance, because of the lower albumin-to-globulin ratio in broilers	Insufficient calcium and symptoms of metabolic bone disease in poultry	Bovera et al. (2015), Ravzanaadii et al. (2012)
A beneficial effect on the blood chemistry measures and carcass traits of broilers	Negatively affect feed efficiency and intestinal morphology in poultry	Biasato et al. (2017), Biasato et al. (2016)
May decrease the use of antibiotics in the poultry industry	A detrimental impact on the nutritional digestibility of organic matter and crude protein	van Huis et al. (2013), Bovera et al. (2016)
The existence of chitin in mealworms has the potential to improve poultry health because it decreases populations of intestinal *Escherichia coli* anddd *Salmonella spp*.	The cost is relatively expensive	Selaledi et al. (2020), Shafique et al. (2021)
Improves growth performance in poultry diet		Hussain et al. (2017)
A positive effect related to mealworms utilization may cause the Gamma glutamyl transferase (GGT) reduction. The high GGT content in birds is a sign of liver illness and issues with bile flow		Ognik and Krauze (2016)
Increased the feed intake, average daily gain, and gain-to-feed ratio in feeding weaning pigs		Jin et al. (2016)
Reducing blood urea nitrogen and boosting insulin-like growth factor in feeding pigs		Jin et al. (2016)

Table 4 Chemical composition of mealworm and soybean meal in livestock feed

Nutrient Component	Mealworm Feed	Soy Feed
Energy, mcal/kg	2.97 [a]	2.51
Protein, g/100g	51.93	44.51
Carbohydrates, g/100g	11.45 [c]	40
Fat, g/100g	21.57	1.84
Fiber, %	7.2	4.79
Ash, %	4.69	6.13
Calcium, % g/kg	4.3	0.33
Phosphorus, %	7.1	0.735
Potassium, %	9.4	2.25
Magnesium, %	2	0.31
EAA g/100 g protein [d]		
Threonine, %	2.71	3.43
Valine, %	3.72	4.09
Methionine, %	1.62	3.18
Phenylalanine, %	1.53	No
Isoleucine, %	4.52	4.64
Leucine, %	4.52	4.64
Lysine, %	1.68	2.83
Arginine, %	3.61	6.17
Histidine, %	2.11	2.51

[a] Hussain et al. (2017)

[b] Bovera et al. (2015)

[c] Son et al. (2021)

[d] Ravzanaadii et al. (2012)

in soybean meal sold in stores. However, in line with the majority of previous findings, the soybean meal's amino acids differed according to the nation of origin (i.e., the region where the beans were grown). Numerous studies have suggested that the amount of protein in the seed has an effect on the amino acid composition of the soybean meal. As a matter of fact, the majority of data show that when the protein concentration in the seed increased, the relative abundance of several amino acids, such as lysine, methionine, cysteine, tryptophan, and threonine, which are frequently growth inhibitors in non-ruminant species, decreased. Overall, the data presented here support the notion that the nutritional value of soybean meal from various origins should be determined by crude protein content while also taking into account variations in the amino acid profile of the protein portion of the meals (Khanal et al., 2023). Figure 5 shows the content of essential amino acids in mealworms (larva stage) and soymeal. The figure makes it abundantly evident how comparable the amino acid compositions of mealworms and soybeans are, as well as how mealworms excel in certain amino acids, including alanine, tyrosine, glycine, valine, and histidine.

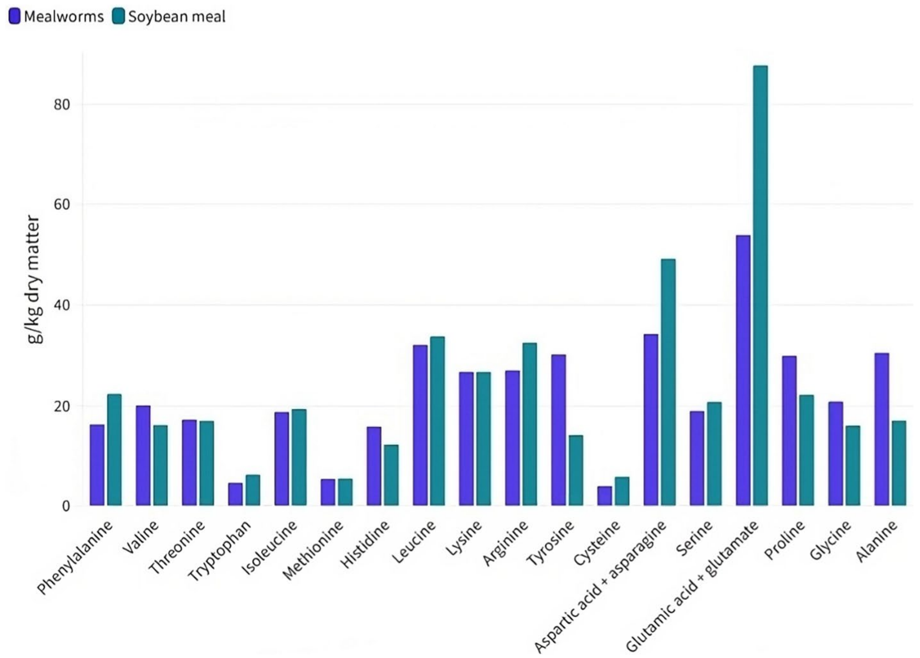


Fig. 5 Essential amino acid content in mealworms and soymeal

5 Life cycle assessment (LCA) and environmental perspectives of mealworms and soy feed

The livestock industry currently uses more than 70% of all agricultural land, and it is responsible for 15% of all greenhouse gas (GHG) emissions produced. GHG emissions and other environmental characteristics are influenced by people's eating choices. A recommended mitigating technique is to switch to proteins from lower-impact animal species (Oonincx & De Boer, 2012). Reducing the impact of protein synthesis from animal sources on the environment has become crucial. As a result, research is being done on protein-rich insects as a potential replacement for traditional protein sources, minimizing both environmental harm and dietary costs. This is owing to insects' low water requirements and the possibility of breeding them on bio-waste substrates and organic side streams, as well as their high nutritional value and high lipid, mineral, and vitamin content (Makkar et al., 2014). Insects (2–122 g/kg mass growth) contribute far less to GHG emissions than beef cattle (2850 g/kg mass gain), while pigs (80–1130 g/kg mass gain) contribute even less. GHG emissions and other environmental factors, such as the use of land or fossil fuels, must be weighed when deciding between different sources of animal protein. According to Oonincx and Boer (2012), the widely used method of LCA has been used to evaluate these characteristics for a range of animal products.

LCA investigates the complex relationship between the environment and a product by evaluating environmental characteristics as well as the possible repercussions connected with a product's life cycle. The LCA of a certain product includes all stages of the life cycle, beginning with the extraction of raw materials from nature and continuing with all industrial and manufacturing processes, consumption, and ultimate product disposal (Lapola et al., 2014). In an LCA, predetermined metrics are measured during the whole life cycle of a product. For mealworms, for example, not only are the direct GHG emissions from respiration analyzed and allocated to a product, but also the GHG emissions from the manufacture and distribution of feed, as well as emissions from the heating of the climate-controlled raising facility (Oonincx & De Boer, 2012). Since it consumes a lot of water, energy, and land and generates a lot of greenhouse gases and ammonia, mass animal production has a negative environmental effect. The production of livestock is responsible for 80% of the GHG emissions produced in the agricultural sector, including emissions from grazing land, energy used to cultivate cereals for feed, and transportation of grain and meat for processing and sale. Mealworms have a 4341 m3/t water footprint per edible ton, which is 3.5 times less than beef and the same as chicken meat (Miglietta et al., 2015). Although producing 1 kg of fresh mealworms requires about the same amount of energy as producing beef or pig, cattle, chicken, and pork require a lot more land (Oonincx & De Boer, 2012). When compared to animals, mealworms produced much less ammonia and GHG (CO_2, N_2O, and CH_4). These gases are particularly significant because of their negative impacts on eutrophication, air quality, and the global climate (IPCC, 2013). Mealworms also require less area to produce 1 kg of edible protein than animals (Nowak et al., 2016). Feed conversion efficiency is another factor to consider while growing animals. Mealworms convert feed as effectively as chickens and utilize nitrogen more efficiently than traditional cattle when fed an appropriate diet. Furthermore, high-protein diets increase larval survival and decrease growth time (Oonincx et al., 2015). Mealworms may thus be raised in a more ecologically friendly manner than cattle while obtaining comparable nutritional qualities, hence encouraging their usage as a protein source for human consumption (Grau et al., 2017). There is little environmental LCA study on insects. In order to assess the potential environmental effects associated with the production of kg of mealworm protein, Dreyer et al. (2021) examined the LCA of yellow mealworms as an organic raw material. Their research shows that the environmental effects of producing 1 kg of edible mealworm protein are equal to 20.4 kg CO_2-eq for global warming potential, 213.66 MJ-eq for non-renewable energy use, 22.38 m^2 for agricultural land occupation, 159.52 g SO_2-eq for terrestrial acidification potential, and 12.41 g P-eq for freshwater eutrophication potential. This study confirmed the potential of mealworms as a sustainable source of protein and provided insights on their environmental impact in comparison to traditional animal production systems (Dreyer et al., 2021). A comparison of the environmental performance of mealworm and soybeans during the production process is presented in Table 5. This indicates that the production of mealworm meal has a greater environmental impact, particularly in terms of energy usage, when compared to soybeans.

Table 5 Comparison of the environmental performance of mealworms and soy during the production process

Factors	Mealworms (Thévenot et al., 2018)	Soy (Wilfart et al. 2016)
Land use (m^2a)	6.35	4.34
Climate change (kgCO_2 eq)	5.77	4.09
Cumulative energy demand (MJ)	217.37	31.17
Eutrophication (gPO_4 eq)	23.03	16.45
Acidification (gSO_2 eq)	39.38	17.61

The biological life cycle of mealworms is brief. The duration of the egg incubation phase is 3–9 days, the larval stage is 26–76 days, the nymph stage is 3–12 days, and the pupal stage is 5–17 days. However, given that larvae are raised in this facility for 11–13 weeks, these figures appear to be underestimated (Li et al. (2013).Mealworm larval meal's environmental performance was assessed using LCA by Thévenot et al. (2018). The results show that the production of mealworm meal (MWM) has a bigger environmental impact than the production of other protein sources utilized in animal feed, especially in terms of energy needs. The effects of one kg of MWM are 141.3 MJ of cumulative energy use, 3.8 kg of CO_2 equivalent for climate change, 25.6 g of SO_2 equivalent for possible acidification, 15.0 g of PO_4 equivalent for potential eutrophication, and 4.1 m^2 of land utilization. In terms of effects per kg of protein, these are more potent than those of soybean or fish meal. Mealworm zootechnical developments are projected to be considerable, which should improve the performance of the latter in terms of the environment, according to a number of recent studies. In order to completely explore the sector from an environmental aspect, prospective and consequential LCAs are required, as shown by a number of significant challenges.

Given the variety of insects that may be used as sources of protein for food and feed, several studies have shown that substituting some insects for soybeans and fish meal is a possibility. Only a few of the adverse characteristics of vegetable feedstock that limit their percentage inclusion in the diet include excessive fiber and non-starch polysaccharide content, inadequate ratios of essential and non-essential amino acids, anti-nutritional components, low palatability, and low digestibility. With a long history of cultivation for food and animal feed, soybean has become a commodity crop with a variety of industrial uses, most notably in the livestock sector. In response to a shift in dietary preferences toward more animal protein, this business has grown dramatically (Oliveira & Schneider, 2016). The huge increase in soybean production and export has had considerable negative effects on the environment since it has changed the land use and land cover in Brazilian biomes both directly and indirectly (Gasparri & de Waroux, 2015). As a result, the global soybean trade is a complex human–environment interaction that may be represented as a metacoupled system. This conceptual paradigm enables concurrent and complementary interactions between remote, adjacent, and local actors (Herzberger et al., 2019). Significant GHG emissions may be produced as a result of the development and production of soybeans. However, evaluating this is challenging, and the results might be very different. The main contributing stage for the environmental consequences of this product system owing to numerous inputs and agricultural methods, notably GHG emissions, was discovered when LCA was utilized to analyze the environmental impact of soybean production. Other important sources of GHG include soil nitrous oxide emissions and changes in land use. Studies have shown that when changes in land use are taken into account, the effects of GHG emissions vary significantly (Humpenöder et al., 2013). Agriculture and land use change (LUC) accounted for 80% of CO_2 equivalent emissions in Brazil in 2005. A naturally occurring GHG in the soil that is 298 times more powerful than CO_2 and associated with the use of nitrogen fertilizers, agricultural waste, and LUC is nitrous oxide (Lapola et al., 2014). Figure 6a, b show the countries that use soybean and mealworm meal as animal feed, respectively.

Fehlenberg et al. (2017) showed that, despite the occasional local importance of other adjacent causes, deforestation in the Chaco appears to be mostly a result of the world's expanding soybean consumption. Landis et al. (2007) confirmed that fertilizer use, crop cultivation, and nitrogen fluxes inside the farm have an impact on air emissions. Future life cycle assessments (LCAs) of corn or soybeans as feed stocks from the American Corn

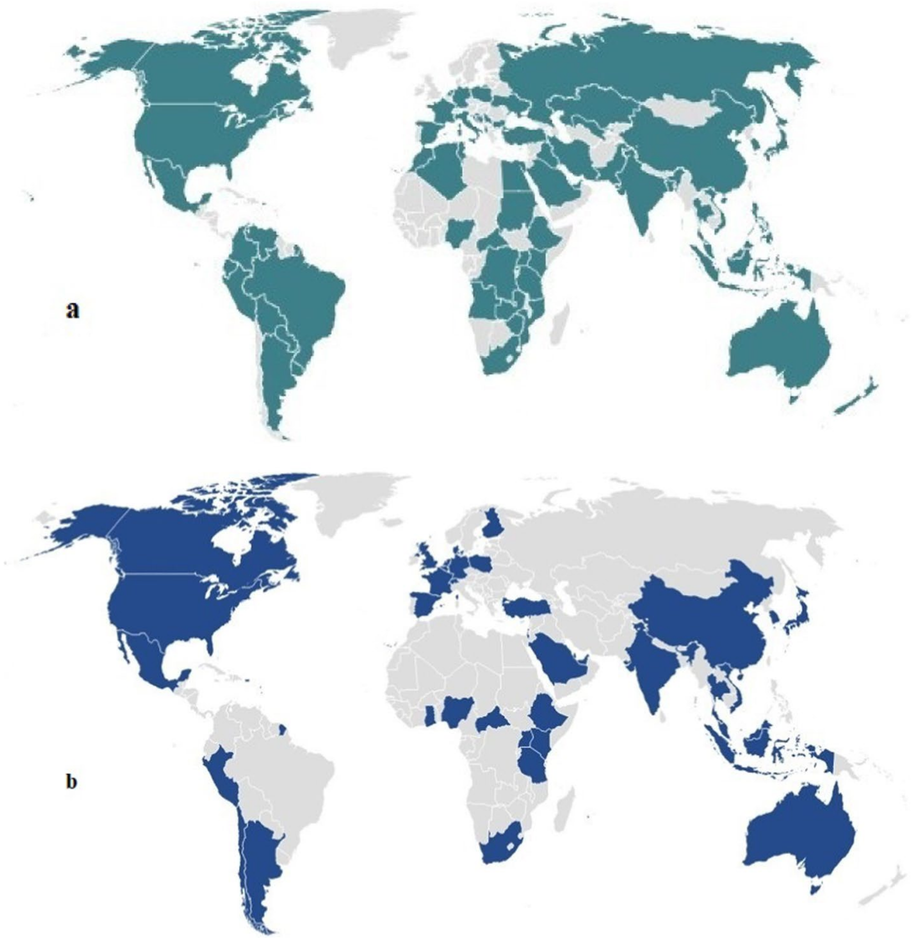


Fig. 6 **a** and **b**: the geographical countries that are using soybean and mealworms as livestock feed

Belt may exclude the contribution of seed production and irrigation, which was less than 0.002% to any of the inventory emissions or energy flows. Effect-decreasing LCAs identify the production stage (creation, use, or disposal) that is expected to have the greatest environmental effect and may suggest ways to reduce those impacts over the course of the product's life. The most environmentally friendly alternative may be chosen with the use of comparative LCAs of potential items (Berardy et al., 2015). The heavy reliance on soybean meal in intensive ruminant production and the crop's negative environmental effects motivate the quest for substitute, protein-rich meals. Four insects—*Alphitobius diaperinus, Tenebrio molitor, Zophobas morio,* and *Acheta domesticus*—were the subject of a study by Toral et al. (2022) to determine their potential as substitute sources of protein for ruminants. The findings suggest that the four insects under study might serve as an alternative to grains for ruminants. Novel feed components, such as insects, can totally replace soybean products, lowering greenhouse gas emissions and the need for arable land for feed production compared to typical diets designed for both chicken lines. It has also been demonstrated that switching from traditional diets to diets that include new components can lessen the additional environmental costs associated with switching to better welfare based cattle systems. It is possible to provide sustainable and nutritionally sound livestock feed in the future by incorporating novel ingredients into diet formulations. This opens up the possibility of custom feeding plans and targeted management decisions that can help chicken systems have a smaller negative environmental impact (Tallentire et al., 2018). Tallentire et al. (2018) proposed novel components to replace conventional feed ingredients that take into account future livestock requirements and environmental challenges. This study looks into the possibility of reducing the overall quantity of soybeans needed in future chicken diets by combining a number of unique components. However, the technologies being developed to manufacture these new components are still in the early stages. Before these components may be used as viable feed alternatives, further study is still needed to characterize them and determine how they affect certain animals.

6 Cost-effectiveness of mealworms and soy feed

Wide swaths of arable land are required for the production of feed soybeans, and the conflict between livestock and people over the use of arable crops is a problem that is growing more and more important globally (Cassidy et al., 2013). According to organic standards, organic livestock systems should be constructed on closed nutrient cycles and farm-based feed production in order to better match consumer expectations (von Meyer-Höfer et al., 2015).

Currently, insect-based products are being considered a valuable source of protein for animals, particularly poultry and fish. Insect meal is still not permitted under organic certification since there is currently no legal basis for its usage in commercial feeds for livestock and poultry in Europe. However, it is likely that the political landscape will shift in the future, making the use of insect protein feasible given the potential ecological benefits and high consumer and farmer approval. This would suggest that biological systems also have valuable potential (Verbeke et al., 2015). Hence, bringing a low-cost domestic mealworm farm to market might provide customers with affordable sources of protein with little negative effect on the environment (Dalton & Al-Zubiedi, 2019). For instance, mealworm production is a more environmentally friendly alternative protein source when a full life cycle assessment study is done since it consumes less land and emits less greenhouse emissions than the production of milk, poultry, pork, and beef (Oonincx & De Boer, 2012). Insect farming, often known as "mini-livestock," is a cutting-edge and unique food source that is abundant in high-quality protein as well as other beneficial nutritional components, including lipids, minerals, and vitamins. It frequently entails low-tech operations and little financial outlay. For the industrial mass production of safe insects and insect products for consumption and for processing into food and feed, rearing, harvesting, and post-harvest methods must be developed (Rumpold & Schlüter, 2013).

Despite the fact that most insects are caught in the wild, insect rearing has been a technique for at least 7000 years. Examples include sericulture (the production of silk), shellac, and subsequently, apiculture (the production of honey) and the manufacture of pharmaceuticals. The cost of producing edible insect protein in large quantities in Europe is considerable and is on par with the cost of meat. For instance, 50 g of freeze-dried mealworms may be purchased in the Netherlands for 4.85 €, including shipping expenses, and it is claimed that this amount will increase to 150 g when rehydrated during cooking. Consequently, depending on their weight after being rehydrated, mealworms are 32.33 €/kg.

The caterpillar Cirina forda, which costs about twice as much as beef, is the most extensively sold edible insect in Nigeria (Rumpold & Schlüter, 2013). Stable production and a competitive price should be guaranteed for mealworms to be used in animal feedings. The insect market is now quite tiny. When compared to soybean meal and fishmeal, which are frequently utilized as sources of protein in the diet of animals, mealworms larvae are less competitive in terms of supply quantity and price (Hong et al., 2020). Table 6 shows a comparison of the prices of mealworm and soybean meal in some countries around the world according to the market price. Technologies related to the production of insects should be developed in order to attain a suitable and economical commercial production, given the interest in and recognized demand for insect protein in food and feed.

For mealworm rearing, according to Li et al. (2013), the durations of the egg incubation, larval stage, nymph stage, and pupal stage are 3–9 days for eggs, 26–76 days for larvae, and 3–12 days for nymphs. However, considering that larvae are raised in this facility for 11–13 weeks, these results appear to be underestimated. They are raised in plastic trays (24 l) with a starting density of 5 larvae/cm^2 on a feeding substrate. Pre-pupal stage larvae are taken for commercial usage since, at this point, they start to lose weight. 90% of the larvae are moved into a cool chamber for storage during harvest time, and 10% are utilized for reproduction, during which the larvae develop into nymphs and finally adults over the course of two weeks. Dynamic ventilation and a cooling system keep the raising chamber at 28 °C and 65% relative humidity. Larvae are fed a composite diet made of cereal flours, meals, wheat bran, and beet pulp twice a week. Larvae are processed into meal and oil after being raised for 11–13 weeks. by sifting to separate larvae from any remaining traces of litter, then blanching in boiling tap water to kill larvae and potential pathogens and to liquefy lipids to increase the extraction rate; next, cold pressing to separate the cake from oil and water; next, drying the cake to obtain dry MWM; and finally, centrifuging to separate mealworm oil from sludge (water leftover from mealworms and the blanching step) (Thévenot et al., 2018).

Although it has been suggested that insect production is sustainable, there are variances in the feed conversion rates of different insect species, and the energy requirements of different farm settings are also different. For instance, the feed conversion rate (FCR) of mealworms, is 3.8–5.8; which is higher than that of *Hermetia illucens* (FCR 1.4–2.6); and can be comparable to that of pigs (FCR of 3.1); as a result, mealworms are less effective

Table 6 Mealworm and soybean meal prices in some countries around the world

Places	Mealworm ($/kg)	Soymeal ($/kg)
USA	12.4	0.47
EU	16.45	0.41
China	8.85	0.47
South Korea	67.5	0.45
Argentina	59	0.39
South Africa	63	0.52
Australia	49.16	0.47
UK	12.55	0.44
India	14.45	0.395
Brazil	39.31	0.357
Nigeria	36.63	0.436
Indonesia	35.82	0.445

at converting feed into body weight than black soldier fly larvae. The energy required to generate mealworms in cold climates may be greater than that required to produce milk or chicken (Ardoin & Prinyawiwatkul, 2021). Naderiboroojerdi & Rajabzadeh (2022) investigated the effects of alternating soybean meal with dry MWM on the carcass characteristics and growth efficiency of broiler chickens. Their findings demonstrated that adding soybean meal in place of dried mealworms at replacement levels of 10% and 15% resulted in greater mean weight gains and daily gains but lower feed intake when compared to other treatments. Moreover, the FCR was significantly lower when compared to the control treatment when using these replacement levels. The results of the experiment demonstrated that broiler chicken performance was greatly enhanced when soybean meal was replaced with worm powder. According to the results of a study by Bovera et al. (2015), mealworms larvae (MWL) meal may totally substitute soybean meal (SBM) in broiler diets throughout the developing stage without having a negative impact on diet palatability. The groups did not differ in their feed consumption. The FCR and protein efficiency ratio are likewise positively impacted by the MWL diet. These findings concur with those made by Ballitoc and Sun (2013), who found a declining trend in the FCR values of broilers fed mealworms from 0 to 10% inclusion in the diet. Nassar et al. (2023) investigated the potential effects of replacing soybeans with different concentrations of MWM in broilers. The findings showed that mealworm utilization increased, which reduced the price of protein and raised profits. Purschke et al. (2018) studied a dry fractionation method to produce mealworm larvae with varied protein compositions.

On the physio-chemical characteristics of the larvae, the effects of post-harvest operations comprising various pre-treatments (blanching, freezing, etc.), drying methods (oven drying, fluidized bed drying, freeze-drying, etc.), and defatting were investigated. Additionally, using sieve classification, the effect of pre-processing on larval disintegration during roller milling was examined. It was discovered that the pre-processing method used had a significant impact on the physico-chemical characteristics of the dried larvae. Dry fractionation is a valuable technique for separating edible insects since it may be used to make protein-enriched flours or concentrates by removing the chitin fraction. The raw material's behavior during dry fractionation will also be influenced by different pre-treatments, such as blanching, drying, defatting, and conditioning, carried out before dry fractionation (Purschke et al., 2018). The development of automated systems for raising, harvesting, processing, and distribution is required to lower costs in the production of edible insects (Vantomme et al., 2012). Additional ways to cut costs include developing low-cost raising substrates, such as those made from organic waste, and improving and automating sanitary practices to control infections and minimize losses. Sanitation practices reduce microbiological contamination and thereby improve the safety of food and feed, in addition to reducing loss throughout the raising process (Vantomme et al., 2012).

Producing plant-derived protein concentrates and isolates with purities > 90% requires the use of wet fractionation methods, which are a common technology. Numerous production steps, including solvent defatting, aqueous extraction at abrasive pH levels and high temperatures, mechanical separation of insoluble matter, isoelectric precipitation, and drying, are frequently used. These steps have a negative impact on the functionality of native proteins and require a lot of water and energy (Tabtabaei et al., 2017). On the other hand, the generation of protein-enriched functional fractions or protein concentrates with retained native functionality but decreased purity can be accomplished by the promising and energy-efficient method of dry fractionation. The separation of the endosperm and bran fractions in the manufacturing of flour using various milling and classification techniques is accomplished utilizing such procedures, which have a long history of effective application in cereal technology. Additionally, a number of studies noted that dry fractionation was effective in separating pulses like lentils, beans, and peas into fractions high in protein and those low in protein (Purschke et al., 2018; Tabtabaei et al., 2017).

Globally, the main criterion for SBM sales is the minimum crude protein (CP) content, which does not accurately reflect the real worth of SBM to the consumer. According to Pope et al. (2023), the SBM value rose on average by $10.27 for swine and $12.62 for poultry per metric ton of feed for each 1% rise in SBM CP concentration from 44.0 to 48.0% (or each 0.065% increase in total lysine from 2.75 to 3.01%). As a result of different processing methods, soybean products' reported chemical makeup differs. Additionally, genetic changes have been seen in the glycine-containing soybean biotypes, which might affect how different they are chemically. Only when diets are properly designed or their anti-nutritive components are eliminated can the use of soybean products in non-ruminant diets result in acceptable performance. In this regard, the utility of any soybean product as a feed element must take into account nutritional content, bioavailability, and anti-nutritive characteristics, as well as their impact on animal performance. It seems that putting soybean proteins through many processing steps increases their quality (Dei, 2011). Figure 7 shows the simplified processing of soybeans and mealworms in animal feeding. About 44% of soybean meal is protein, making it a high-quality plant protein source with a stable amino acid (AA) profile. However, improperly processed SBM may include lectins and trypsin inhibitors, which are anti-nutritional substances. By heating the soybeans during processing, these elements can be rendered inactive. Due to insufficient or excessive heating, these heat processing parameters must be closely controlled to prevent impaired AA digestibility (Kim et al., 2012). As is common knowledge, more than 70% of all operational expenses in the animal production industry are related to feed expenditures. Insects may be used in place of fishmeal and soybean meal at different levels, according to the literature. Mealworms, which have a high crude protein content and a low crude fat content, are one form of bug that may be used as food and feed. Using mealworms in feed is an excellent alternative in terms of nutritional value and cost if it is effectively produced.

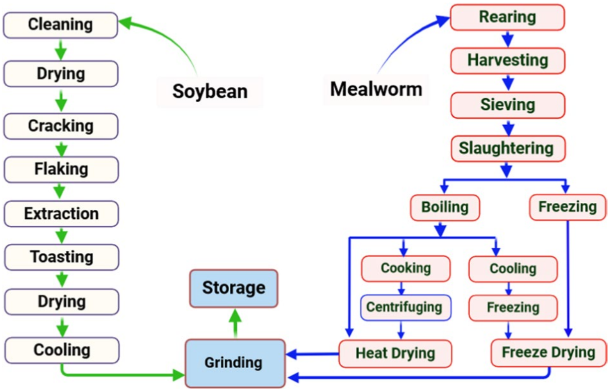


Fig. 7 The processing of mealworms and soymeal for livestock feed

7 Contamination effects of mealworms and soy feed for livestock

Insects have become one of the most cutting-edge food sources for both humans and animals in recent years. Eating insects is a significant step in the drive to diversify protein sources and ensure global food security (Patel et al., 2019). Concerns over microbiological safety, toxicity, unpalatability, and inorganic chemicals are among the food safety concerns relating to insects. The design of the raising system must mitigate disease and reduce susceptibility to potential diseases in order to commercialize the use of edible insects as food or feed. Additionally, the best preservation techniques must be identified, human risks must be avoided, and human hazards must be avoided. Therefore, it is necessary to create and enforce risk recommendations and hygienic requirements for each species (Van Huis et al., 2013). Insects are often maintained in small, cramped areas, similar to many intensive production techniques; sufficient room should be supplied to farmed insects to guarantee animal welfare and reduce health problems. Like other insects, mealworms often congregate in groups. So, in raising facilities, ideal circumstances are sought after in order to reduce mortality and boost output (Van Huis et al., 2013). Despite the assertion that eating edible insects has not been associated with any serious health problems, it is arguable that customer confidence and a product's perceived safety are highly interrelated. The nutrition and moisture found in insects make them an ideal setting for microbial survival and development (Klunder et al., 2012). The likelihood of zoonotic diseases is thought to be low, nevertheless, because humans, cattle, and insects have quite different taxonomic backgrounds. However, improper disposal of waste, handling of insects in an unclean manner, and direct contact between insects being raised and outside pollutants all have the potential to enhance the risks of zoonotic infection (Van Huis et al., 2013). The microbiological safety of meals made from insects that are meant for human consumption is still up for dispute (Belluco et al., 2015). By removing pathogen carriers and reservoirs from the food chain, insect farming can help reduce the frequency and spread of a few infectious illnesses, especially those that are foodborne. The majority of entomopathogens does not contribute to the zoonotic disease epidemic and do not threaten people (Doi et al., 2021). It is extremely improbable that edible insects would serve as disease vectors (Yates-Doerr, 2015). The danger of zoonotic disease transmission is minimal in industrially farmed insects since they are fed agricultural byproducts and plant-based products. Eating and using edible insects is safe because entomopathogens cannot infect mammals across species boundaries (Doi et al., 2021).

Mealworms are fed and consumed by humans without removing the gut, so any bacteria present there—including pathogens—are transferred to them. Using techniques that are both culture-dependent and culture-independent, the microbial profile of mealworms that have been raised commercially has been examined. Mealworms, whether freeze-dried or fresh, contain a lot of aerobic bacteria when the larvae are ground up (up to 8 log CFU/g), according to many culture-based studies that counted the amount of microbial colony forming units (CFUs). This exceeds what is deemed to be equivalent guideline levels for minced meat (Vandeweyer et al., 2017). 7.2 log CFU/g enterobacteria, 3.6 log CFU/g endospores, and as many as 5.3 log CFU/g yeast and fungus were also present in the crushed larvae (Klunder et al., 2012; Vandeweyer et al., 2017). When the larvae were not thoroughly ground before testing the microbial load, the log CFU/g values dropped to under two; however, this might be due to the entrapment of microorganisms in the gut, which would impede their culture although they would still be present in the finished product (Garofalo et al., 2017). The high microbial load in the mealworms did not, however, include common food-borne diseases such as *Listeria monocytogenes* or *Salmonella spp*. The overall bacterial load and enterobacteria count were both dramatically decreased by a brief heating or blanching phase (Klunder et al., 2012). Proteobacteria (35.9%), Firmicutes (31.1%), and Actinobacteria (26.9%) were the three bacterial phyla that predominated in the mealworms in one study (Engel & Moran, 2013). According to Garofalo et al. (2017), Tenericutes (44.2%), Proteobacteria (39.22%), and Firmicutes (13.9%) were the three most prevalent bacterial phyla. Jung et al. (2014) confirmed the dominance of Tenericutes (36.6%), Proteobacteria (34.1%), Firmicutes (26.2%), and Spiroplasma (38.7%) at the genus level. When insects are raised in large numbers, reproductive manipulators like Spiroplasma, Wolbachia, and Rickettsia, which are known to infect a wide range of insects, might interfere with breeding plans and pose a threat to livestock and consumers. However, because of the possible protective properties of these bacteria, they cannot be completely eradicated (Jung et al., 2014).

Mealworm has a high nutritional value and is a suitable source of protein for poultry and other agricultural animals (Jin et al., 2016). However, this beetle is particularly hazardous to both human and animal health because it releases mutagenic carcinogens (benzoquinones). Long-term exposure to mealworm infested items can cause respiratory allergies, and the beetle has been linked to canthariasis epidemiology (Gałęcki et al., 2020). Canthariasis is referred to as the invasion of beetle larvae on a living organism during which, at least briefly, the larvae feed on the tissues, body fluids, or food consumed by the host. The first three phases of insect development occur within the host, following which the imagoes leave the body to complete the life cycle. There have been very few reports of mealworm-related canthariasis (Gałęcki et al., 2020). Additionally, it's possible that insects might transmit parasitic diseases. Due to the biological peculiarities of the host, it appears that entomopathogenic parasites are unable to complete their whole life cycle in people or cattle. For foodborne infections such as tapeworms (*Hymenolepis* spp.), lancet liver flukes (*Dicrocoelium dendriticum*), and nematodes (*Spirocerca lupi*), insects can also serve as intermediate hosts. At certain points in their life cycles, insects can also serve as mechanical vectors for various developmental stages of vertebrate parasites. Insect farming raises severe concerns about the mechanical transmission of parasites. According to research, insects can spread protozoa (Gałęcki & Sokół, 2019; Gałęcki et al., 2023). Also to be considered is the possibility that insects themselves may contribute to the etiology of illness. Canthariasis is a disease that is brought on by beetles in the Tenebrionidae family, such as smaller mealworms and yellow mealworms. A mite infestation can occur in an insect farm (Maciel-Vergara et al., 2021). Diseases caused or transmitted by mealworms are discussed in Table 7.

In order to reduce the number of harmful microorganisms in farmed insects, effective treatments, such as high-temperature processing, are required (Klunder et al., 2012; Mutungi et al., 2019). These methods get rid of the germs and pathogens that cause food to deteriorate. Pesticides, antibiotics, detergents, and other pollutants must not be present in insect meals or final products. Whereas edible insects represent a distinct class of farmed animals and a new link in the food chain, their production is fraught with the same issues and difficulties as conventional livestock raising and meat production. (Gałęcki et al., 2023). Enterobacteriaceae and spore-forming bacteria have been discovered in the fresh insects; However, boiling the insects for five minutes only destroyed the Enterobacteriaceae, not the spore-forming bacteria (Klunder et al., 2012). It was discovered that the cooked insects kept well for more than two weeks in a refrigerator set to 5 to 7°C; unless they were dried or acidified, they only lasted for about a week at room temperature. Additionally, it was shown that the insufficient heat transmission to

Table 7 A summary of mealworms and their role in the transmission of diseases to humans and animals

Animal disease caused by Mealworms					Human disease caused by Mealworms			
Disease	Pathogen	Animal host	Region's distribution	Reference	Disease	Pathogen	Region's distribution	Reference
Salmonellosis	*Salmonella spp.*	Animals	Worldwide	Jensen et al. (2020)	typhoid fever	*Salmonella spp.*	Worldwide	Jensen et al. (2020)
Crypto	*Cryptosporidium spp.*	humans, and animals	Worldwide	Dixon, (2015)	cryptosporidiosis	*Cryptosporidium spp.*	Worldwide	García-Livia et al. (2020)
Gregarine disease	*Gregarine spp.*	Molluscan	The North Atlantic, and the White Sea	Zakariah et al. (2019)				
Hymenolepiasis	*hymenolepis diminuta*	Rats	Worldwide	Xie et al., 2017	Hymenolepiasis	*hymenolepis diminuta*	Worldwide	Panti-May et al. (2020)
Listeriosis	*listeria monocytogenes*	monogastric animals	Worldwide	Mancini et al. (2019)	Listeriosis	*listeria monocytogenes*	Worldwide	Wang et al. (2017)
Mastitis	*Staphylococcus aureus*	cattle, sheep, goats, and horses	Worldwide	Mamtimin et al. (2023)	Staphylococcal Infections	*Staphylococcus aureus*	Worldwide	Lozano et al. (2016)
Mastitis	*Serratia marcescens*	Animals, invertebrates and plants	Worldwide	Ishii et al. (2014)	Nosocomial infections	*Serratia marcescens*	Worldwide	Kim et al. (2015)
Pneumonia	*Rhodococcus equi*	horses and foals	Sub-Saharan Africa	Vázquez-Boland et al. (2013)	Rhodococcus equi infection	*Rhodococcus spp.*	Worldwide	Stewart et al. (2019)
Diarrhoea	*E. coli*	Animals	Worldwide	Allocati et al. (2013)	clinical infections	*E. coli*	Worldwide	Allocati et al. (2013)
Botulism	*Clostridium botulinum*	Humans, and various *animals*	Worldwide	Kooh et al. (2020)	Botulism	*clostridium botulinum*	Worldwide	Kooh et al. (2020)
Enterotoxemia	*Clostridium perfringens*	humans and livestock	Worldwide	Lu et al. (2021)	food poisoning	*Clostridium perfringens*	Worldwide	Lu et al. (2021)

the interior tissues made roasting ineffective for killing Enterobacteriaceae on its own. This is why it was suggested that, before roasting, there be a brief blanching phase in hot water. Enterobacteriaceae were also shown to be rendered inactive by another lactic acid fermentation procedure. However, this technique did nothing more than maintain a low level of spore-forming bacteria. Although Enterobacteriaceae can be killed by heat treatment, spore-forming organisms could need a more intensive heat treatment method, such as canning. Blanching and subsequent roasting for around 10 min reduced the overall number of microorganisms on entire insects by 5 log cycles while also reducing the number of spores by 2 log cycles. Following these processes, the residual spores can be contained using the right packing and by enlisting other adjustments, such as acidity, along with cold storage (Klunder et al., 2012; Mutungi et al., 2019). Additionally, techniques such as smoking, brining, frying, steaming, boiling, roasting, toasting, and drying aid in the creation of safe goods.

According to Klunder et al. (2012), in boiling samples of the house cricket (*Acheta domestica*) and mealworm, Enterobacteriaceae were only found in concentrations of less than 10 CFU/g. The samples underwent a brief heat treatment after being killed by boiling water, which, according to the literature, successfully eradicated the enterobacteria. Lactic acid bacteria (LAB) are widely distributed in nature, significant in food and biotechnology, and beneficial to human health. LAB has positive effects primarily on the gut microbiota, enhancing intestinal peristalsis and halting the development of dangerous bacteria. Additionally, they have an impact on the immune system, facilitate vitamin formation, and aid in the absorption of minerals like calcium and iron. Due to the lactic acid bacteria's extensive availability in the environment, a sizable number of these bacteria were found in recently dead insects (Adámek et al., 2018). LAB was found in insects. Vandeweyer et al. (2015) analyzed recently deceased insects and discovered that mealworm larvae contained 2.5×10^7—1.6×10^8 CFU/g. Whereas Stoops et al. (2016) discovered mealworms to have 1.0×10^7–4.0×10^8 CFU/g. While Adámek et al. (2018) discovered 2.8×10^6CFU/g in the lesser mealworm, numerous insect species can collect biological or chemical pollutants that might be harmful or anti-nutritional. This is aided by the presence of natural habitats, feeding patterns, and human activity (such as mining and agriculture) adjacent to areas where insects may be gathered. Insects also act as hosts or vectors for illnesses that affect vertebrates and can result in life-threatening infections (Mutungi et al., 2019). As a part of their defense strategies, certain insect species release chemicals with potentially harmful effects (Dzerefos et al., 2013). In relation to mealworms, focus has been placed on benzoquinones, which adult beetles release into their stomach cavity. Benzoquinones have been shown to have hazardous consequences. The findings do not apply to mealworm larvae but rather to adult insects (beetles). Regarding the defense mechanisms of mealworm larvae, adult mealworms and other species of insects are fatally affected by acidic methanolic extracts of mealworm larvae (Turck et al., 2021). The hazards may be reduced if the insects were raised in controlled surroundings and public health issues were taken into account when choosing the substrates for raising them or when harvesting them from the wild. Post-harvest processing continues to be the sole method for addressing these safety issues because it is typically impossible to ensure the gathering of hazard-free insects (Mutungi et al., 2019). As a result, it's essential to follow procedures that eliminate or drastically minimize the pathogens in insects in order to ensure a safe product. Although insects have some special qualities that make them an excellent candidate for use as an effective and environmentally friendly source of protein in animal production, the risks associated with them must be considered. As a result, minimizing these hazards will result in a protein substitute that is affordable, secure, and ecologically friendly (Berardy et al., 2015).

As a result of cultivating insects in large numbers for food and feed, toxic chemicals such as heavy metals that arise from contaminated insect diets may accumulate. Testing of a range of chemical contaminants on commercial mealworms revealed levels that were either similar to or lower than those reported in beef (Poma et al., 2017). But using polluted waste streams as feed can encourage pesticide buildup (Houbraken et al., 2016). Maintaining high levels of quality assurance and hygiene in the breeding and processing of mealworms is crucial due to their high nutritional content, low cost, and environmental friendliness, and to ensure that they are free of diseases and contaminants. To reduce the risk of pathogens and toxins and provide a safe product, routine cleaning procedures and the use of clean, uncontaminated feed during mealworm reproduction can help (Berardy et al., 2015). For numerous reasons, reducing infections in mealworms is important to ensure the safety of the final product, as these dangerous microbes must be eliminated or minimized. For instance, many countries have laws governing the security of food goods, including insects meant for feed or food. To comply with these laws and guarantee that the product passes safety standards, mealworms must have fewer infections. Therefore, edible insect farming has the potential to grow into a lucrative industry that significantly increases the overall sustainability of food systems if the proper regulations are put in place and food safety standards are met. This means that as the edible insect business grows, many obstacles must be overcome. Once strict food safety regulations are put in place and entomophagy becomes more widely accepted, edible insect farming might become a profitable industry that supports the sustainability of food systems (Żuk-Gołaszewska et al., 2022). Pesticides are chemicals that are used to control a variety of pests (Choudhary et al., 2018). Despite the fact that their use is crucial for agricultural yield, their excessive use also pollutes our environment (Hashimi et al., 2020). Respiratory, integumentary, cardiovascular, gastrointestinal, and neurological issues are some of the adverse health impacts linked to the use of various pesticides. More than 2000 different pesticide poisonings due to acute causes occurred in Morocco between 2008 and 2014 (WHO, 2019). Cancer is one of the more difficult long-term impacts to directly link to pesticide usage. The eating of food containing residues beyond legal limits has effects on one's health as well (Joko et al., 2020; Sarkar et al., 2021). Livestock feeds are frequently contaminated with pesticides by a variety of factors, including environmental pollution, insect and microbe activity, and human handling. To improve the quality and competitiveness of animal products, animal feed may also contain endogenous poisons, which are mostly the result of pesticide application. Animals are frequently given feed and fodder that contains pesticide residues, which pass through the body after consumption. These chemicals can be obtained by animals through tainted feed and water. Accordingly, because these pesticides are lipophilic, milk and other fatty foods are the main sources of their buildup (Choudhary et al., 2018). The use of pesticides has been linked to several harmful side effects in humans, animals, and birds, including the development of cancer, teratogenicity, immunosuppression, embryotoxicity, infertility, and birth abnormalities, as well as a number of other conditions, including hepatotoxicity, nephropathy, mutagenicity, and hypersensitivity (Choudhary et al., 2018). Reproductive toxicants, or endocrine disrupters are terms used to describe pesticide residues that have a negative effect on the reproductive system. By acting at several places, such as the brain, pituitary, and reproductive organs, these toxins modify or disrupt the milieu of reproductive hormones (Choudhary et al., 2018). These harmful substances are ingested by people through their environment, including the water, air, and agricultural goods. However, despite the fact that they are eliminated in various ways or retained in the tissues of both people and animals, their negative effects continue unabated. They depress every human organ, including the brain, kidneys, skin, gastrointestinal system, liver, lungs, and spleen. They result in a variety of illnesses, tumors, mutations, and death (Hashimi et al., 2020). Pesticides can change the microbiomes of a wide range of creatures, from insects to mammals, by affecting a number of characteristics of the animal microbiome, including the taxonomic makeup of bacteria, bacterial biodiversity, and bacterial ratios. Animal immunity is reduced by the microbiome alterations brought on by pesticides. Pesticide side effects may be a global issue for pollinators. Another potential drawback of pesticides is their impact on the intestinal microbiota of bees and bumblebees, which makes the body more susceptible to pathogenic microflora and ultimately kills insects. Pesticides can also have an impact on vigor, mate choice, and offspring traits (Syromyatnikov et al., 2020). In addition, the massive spraying of pesticides severely suppresses animals, birds, and soil organisms (Hashimi et al., 2020). When agricultural chemicals are used correctly and in accordance with instructions, the adverse effects of pesticides on the environment are reduced (Choudhary et al., 2018).Due to all of these factors, it is crucial to follow all guidance and suggestions made about pesticides by the appropriate authorities in order to preserve a safe and healthy environment.

8 Conclusion

In light of global challenges such as population growth, food insecurity, and environmental strains, finding sustainable protein sources is imperative. Insects, long embraced as a dietary staple in many regions, offer a promising solution due to their efficient resource utilization and nutritional value. Among these, mealworms stand out as a commercially significant option for both food and feed production. Our review underscores their potential as a cost-effective and environmentally friendly alternative to traditional livestock feed, with lower ammonia and GHGs. However, the literature highlights concerns regarding insect-borne illnesses, necessitating careful management.

This review has practical applications across agricultural, livestock, and environmental sectors. It offers insights into replacing soy with mealworms in livestock feed, aiding farmers in exploring environmentally friendly protein sources while meeting nutritional needs. By assessing environmental aspects like energy use and emissions, it guides policymakers and stakeholders in evaluating sustainable feed options and shaping environmental policies. Additionally, understanding the economic implications of mealworm-based feed helps decision-makers in agriculture and food industries. Mealworms, potentially sourced from organic waste, align with circular economy principles, supporting sustainable waste management. Ultimately, the review informs stakeholders about the environmental impact of adopting mealworms, fostering informed decisions for sustainable agriculture.

Through a comprehensive analysis, we explored the significance of mealworms as feed sources, their nutritional profile, and their potential to replace soy in animal feed while considering environmental impacts. While mealworms offer substantial benefits, optimizing production processes remains critical to ensure affordability and safety.

Recommendations include conducting additional comparative studies to understand the environmental impacts of replacing soy with mealworms in livestock feed. These studies should consider various factors such as livestock types and geographic regions for comprehensive insights. Encouraging pilot projects can assess the practicality and scalability of mealworm-based feed, while fostering dialogue among stakeholders is crucial for promoting knowledge exchange and facilitating sustainable practices.

Acknowledging limitations, such as data variability and the review's scope, future research should standardize methodologies and explore additional environmental factors. Long-term effects of replacing soy with mealworms on soil health and food security need monitoring. Future prospects involve investigating the nutritional quality of livestock products, technological innovations in mealworm farming, and developing policy frameworks to support mealworm-based feed integration. Addressing these recommendations, limitations, and future prospects can advance knowledge and promote the sustainable adoption of mealworm-based feed in livestock farming practices. Further research is needed to develop cost-effective and eco-friendly processing methods, facilitating the widespread adoption of mealworms as a sustainable protein source for livestock.

Author contribution statement SAS—conceptualization, methodology, validation, formal analysis, resources, writing—original draft, writing—review and editing, visualization, data curation, software, project administration, investigation, funding acquisition, supervision. WE—writing—original draft, formal analysis, visualization. IU—review, formal analysis. MH—writing—original draft, formal analysis, visualization. ZCP—methodology. BY—Review and editing.

Funding Open Access funding enabled and organized by Projekt DEAL. The open access publishing fee is covered under the agreement between the DEAL Consortium and Springer and Springer Nature upon acceptance due to Shahida Anusha Siddiqui being affiliated to the Technical University of Munich.

Data availability No data is available.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors and Affiliations

Shahida Anusha Siddiqui[1,2] · **Wadah Elsheikh**[3] · **İlknur Ucak**[4] · **Muzaffar Hasan**[5] · **Zerlina Cleantha Perlita**[6] · **Bara Yudhistira**[7]

✉ Shahida Anusha Siddiqui
S.Siddiqui@dil-ev.de

[1] Campus Straubing for Biotechnology and Sustainability, Technical University of Munich, Essigberg 3, 94315 Straubing, Germany

[2] German Institute of Food Technologies (DIL e.V.), Prof.-von-Klitzing Str. 7, 49610 Quakenbrück, Germany

[3] Department of Meat Production, Faculty of Animal Production, University of Khartoum, 13314 Khartoum, Sudan

[4] Faculty of Agricultural Sciences and Technologies, Department of Animal Production and Technologies, Nigde Omer Halisdemir University, 51240 Niğde, Turkey

[5] Centre of Excellence for Soybean Processing and Utilization, ICAR-Central Institute of Agricultural Engineering, Bhopal, MP, 462038, India

[6] Nutrition Science Department, Faculty of Medicine, Diponegoro University, Kota Semarang 50275, Indonesia

[7] Department of Food Science and Technology, Faculty of Agriculture, Sebelas Maret University, Surakarta 57126, Indonesia