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Feature Article

Multiple Applications of Yellow Mealworm (*Tenebrio molitor* L.) Reared on Plant-Based Substrates: Circular Agriculture, Farmed Animal Feed, and Other High-Value Products

Meng-You Hsieh[1,*], Wen-Bin Feng[1,*], Pei-Chen Hsu[2], Yaw-Jen Dong[2],
Ya-Lin Lee[3], and Hsien-Tzung Shih[4,**]

Abstract

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With the continuous growth of the global population, pressures on food supply and challenges in agricultural waste management have become increasingly severe. Insects have been increasingly recognized as a key solution to these issues. As biological agents capable of converting organic waste, insects can transform agricultural by-products and food processing residues (resources that are otherwise difficult to be used) into valuable outputs. This process not only promotes resource recycling and reduces the carbon footprint but also offers a sustainable alternative to conventional protein sources in animal feed, such as soybean meal and fishmeal, thereby supporting the sustainable development of both agriculture and animal husbandry. In the application of insects as feed ingredients for farmed animals, they provide high levels of protein and fat, making them a promising substitute for conventional animal feed components. Their cultivation requires fewer resources, has a short production cycle, and demands less space compared to traditional livestock, which positions insect farming as an efficient and environmentally friendly model in resource utilization. In addition to larval biomass, insect frass, the excreta and residual substrate generated during yellow mealworm rearing, constitutes an important by-product. Rich in nitrogen, phosphorus, chitin, and beneficial microorganisms, frass has shown potential as an organic fertilizer that enhances plant growth. Its application further reinforces the role of mealworm farming in sustainable waste recycling systems. This study takes the yellow mealworm (*Tenebrio molitor*) as a case study to explore its feasibility and advantages in decomposing plant-based residual materials and analyzes key considerations in its breeding process. In addition, this study assesses the potential of yellow mealworm larvae as a raw material in animal feed, including its nutritional value and practical application cases. It also reviews the prospects of using insect biomass and by-products in the development of high-value end products. The aim of this research is to provide a comprehensive understanding of the impact of resource insects on global food supply and environmental sustainability. Compared to traditional crop and livestock farming, insect farming exhibits

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[*] These authors contributed equally to this study.

[**] Corresponding author, e-mail: htshih@tari.gov.tw

[1] Assistant Research Fellows, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.

[2] Associate Research Fellows, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.

[3] Research Fellow, Crop Genetic Resources and Biotechnology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.

[4] Research Fellow and Division Director, Applied Zoology Division, Taiwan Agricultural Research Institute, Taichung City, Taiwan, ROC.

higher efficiency in resource utilization and significantly lower environmental impact, making it one of the green industries aligned with the United Nations Sustainable Development Goals (SDGs).

Key words: *Tenebrio molitor*, Plant-based substrates, Circular agriculture, Farmed animal feed, High-value applications.

INTRODUCTION

In 2022, the global population surpassed 8 billion, with projections indicating an increase to 10 billion by 2058 (Ritchie *et al*. n.d.). This rapid population growth has substantially heightened the global demand for crop production, as well as for food and livestock products (Verbeke *et al*. 2015). According to FAO (2024b), global production of crops, meat, eggs, and milk in 2022 reached 96, 361, 87, and 897 million tons, respectively, reflecting increases of 56%, 55%, 70%, and 61% compared to the year 2000. To meet the rising demand for animal-based proteins, the need for feed ingredients such as grains, soybean meal, fishmeal, and fish oil has also intensified. However, competition for limited arable land and water resources limits crop production for animal feed, further exacerbating food security challenges. Additionally, overfishing has restricted the availability of fishmeal, a critical component in livestock feed. These challenges underscore the urgent necessity to establish sustainable agricultural production systems, supported by relevant technologies and policy frameworks, which have become a top priority for governments worldwide.

FAO (2024a) emphasizes that reducing post-harvest losses is essential for enhancing the sustainability of food systems. According to UN (2020), approximately 13% of global food is lost between harvest and retail, while 19% of available food is wasted at the consumer level. In 2022, global food waste reached 105.2 million tons, primarily originating from food services, retail, and households (UNEP 2024). It is projected that by 2050, global waste generation will increase to 3.4 billion tons annually, representing a 70% increase of that in 2016, with 44% attributed to food waste and agricultural production residues (Kaza & Yao 2018).

Agricultural residues, also referred to as agricultural by-products, include leftover materials from agricultural production processes, such as rice straw, soybean meal, animal manure, and shrimp and crab shells. These residues are rich in cellulose, lignin, proteins, amino acids, minerals, and trace elements. However, conventional disposal methods, such as landfill burial and open field burning, contribute to greenhouse gas emissions (such as carbon dioxide, methane, and nitrous oxide), leading to air pollution and water contamination, which pose risks to ecosystems and human health (Koul *et al*. 2022).

One of the ultimate challenges of the twenty-first century is to ensure sufficient food production from healthy ecosystems for a growing global population. Establishing sustainable plant and animal production systems has become a critical strategic issue for global agriculture (Shih *et al*. 2021). A promising approach to this challenge involves incorporating insect species into agricultural production chains, utilizing them to decompose food waste and agricultural by-products, and converting them into economically valuable insect products such as animal feed, pet food, and industrial materials. This concept has emerged as one of the most popular topics in circular agriculture.

Insects are among the most ecologically diverse taxonomic groups, with a widespread global distribution. Stork (2018) notes that at least one million insect species have been formally described, with an estimated five million species yet to be discovered. Throughout Earth's long geological history, insects have continuously existed and evolved, playing a crucial role in shaping global biodiversity (Engel 2015). Different insect taxa occupy various ecological niches, providing numerous ecosystem services. These include roles as decomposers (such as larvae of houseflies, flesh flies, black soldier fly (BSF), and scarab beetles), pollinators (such as adults of bees, bumblebees, and flower flies), herbivores (such as grasshoppers, larvae of butterfly and moth), predators (such as lacewings and mantids), and parasitic predators (such as parasitoid wasps). Additionally, insects serve as secondary producers, forming a crucial food source for insectivorous animals, engaging in symbiotic relationships with microorganisms, and acting as vectors for plant and animal pathogens (such as leafhoppers, aphids, planthoppers, and whiteflies).

The loss of insect biodiversity can result in a significant decline in global biodiversity. Approximately 75% of the world's crop species depend on insect pollination (Jankielsohn 2018; Wagner 2020). A reduction in insect diversity, especially pollinators, would pose a severe challenge to the survival of animals that depend on crops for sustenance. Therefore, insects are vital for maintaining biodiversity and ecosystem health, with the potential to contribute to agriculture, human and animal diets, medicine, and bioconversion processes. Their utilization aligns with the Sustainable Development Goals (SDGs) of United Nations (Barragán-Fonseca 2024).

This report reviews the global integration of insects into circular agricultural systems by using *Tenebrio molitor* Linnaeus (yellow mealworm, YM) as an example. The aim is to provide insights into the contributions of insect farming to animal nutrition and environmental sustainability by focusing on three major aspects: (1) the role of YMs in circular agriculture, (2) their applications in livestock farming, and (3) the emerging high-value uses of their biomass and by-products across various industries. Through mass breeding, insects are utilized as livestock feed, while their products and by-products are processed into materials of high-value end-product. Compared to crops or livestock, insect farming is a relatively energy-efficient and low-pollution, sustainable industry that aligns with the SDGs of United Nations. As for the application of insects in human food and pet food, this will be addressed in a separate review paper.

THE REASON FOR INSECTS TO SERVE AS A SUSTAINABLE FOOD SOURCE

Insects have long been an integral component of human diets across various cultures and geographical regions. Their nutritional composition is rich in protein, essential fatty acids, vitamins, minerals, and other bioactive compounds (Abdulsalam *et al*. 2019). Research indicates that early hominids used bone tools to collect and consume termites (Backwell & d'Errico 2001). Hardy *et al*. (2017) discovered 1.2-million-year-old fossils of *Homo* sp. from Spain, with dental calculus residues that contained insect fragments, plant fibers, meat, pollen, and fungal spores, providing direct evidence of entomophagy among early human ancestors. Additionally, historical records indicate that insect consumption was documented in China as early as 3,000 years ago (Chen *et al*. 2009). Insects for human food and medicine have been integral to cultural development throughout history. Although European cultures historically rejected entomophagy, Carl Linnaeus recorded that Europeans consumed larvae of bees, hornets, and ants in his zoological lectures as early as 1740 (Svanberg & Berggren 2021). Currently, entomophagy is practiced by over 2 billion people across 130 countries and more than 3,000 ethnic groups, incorporating between 1,000 and 2,200 insect species into human diets (Jongema 2017).

Beyond human consumption, insects also serve as a natural food source for many animals. Humans have developed animal feed formulas through long-term observation of the insect feeding habits of wild animals and semi-captive livestock. For instance, insects make up approximately 6% of the diet of wild cats (Veldkamp *et al*. 2012). Basuony *et al*.

(2005) reported that insects, including the American cockroach (*Periplaneta Americana* (Linnaeus)), beetles, grasshoppers, and mantises, were the second most abundant food component found in the stomachs of red foxes (*Vulpes vulpes* (Linnaeus)) in Egypt. Additionally, aquatic insects from Diptera, Trichoptera, Odonata, Hemiptera, and Coleoptera (both adult and larval stages), as well as terrestrial Hymenoptera insects from the families Vespidae (wasps) and Formicidae (ants), are common natural food sources for omnivorous and carnivorous fish. Fragments of insects from Hymenoptera, Diptera, and Coleoptera have also been identified in the digestive tracts of marine and saltwater fish (Goutham-Bharathi *et al*. 2013; Henry *et al*. 2015; Nogales-Mérida *et al*. 2019). Henry *et al*. (2015) reviewed studies on replacing fishmeal with insects in aquaculture feed, suggesting that interdisciplinary collaboration between entomologists and fish nutritionists is crucial to determine the optimal substitution ratio and the potential benefits of insects in improving fish health.

ADVANTAGES OF INSECTS IN CIRCULAR AGRICULTURE AND AS AN ALTERNATIVE PROTEIN SOURCE

Compared to conventional livestock, insects exhibit higher growth rates and reproductive capacities, enabling for stable production and mitigating seasonal fluctuations in crop and aquaculture supply. As poikilothermic animals, insects do not require additional metabolic energy for thermoregulation, enabling a higher proportion of energy intake to be allocated to growth. Consequently, insects demonstrate superior feed conversion rates (FCRs) compared to conventional livestock. The FCRs of commonly farmed insect species, such as *Acheta domesticus* (Linnaeus) (house cricket), *Hermetia illucens* (Linnaeus) (BSF), and *T. molitor* (YM), range from 1.50 to 2.08, which are comparable to aquaculture species (1.0–2.4) and broiler chickens (1.9) but significantly lower than that of pigs (2.7–5.0) and cattle (6.0–10.0) (Fry *et al*. 2018; Bawa *et al*. 2020; Deruytter & Coudron 2022).

Moreover, insects exhibit exceptionally high edible biomass yields, with nearly 100% of their body mass being consumable, in contrast to approximately 50% for conventional livestock, making them a highly efficient source of animal protein. From an environmental perspective, insect farming imposes a significantly lower ecological footprint compared to conventional livestock production, including reduced greenhouse gas emissions, lower land and water requirements, and improved energy efficiency (Lange & Nakamura 2021; Kim *et al*. 2022; Jafir *et al*. 2024). Moreover, insects can be reared on low-cost feed substrates, including agricultural by-products and food processing residues, with minimal space and operational costs compared to conventional meat production. This reduces reliance on soybean meal and fishmeal in livestock industries that contributes to the conservation of terrestrial and marine ecosystems while mitigating competition for food resources between human and livestock populations.

As a sustainable alternative protein and a key component of circular agriculture, insect farming aligns with multiple UN-SDGs, including SDG1 (No Poverty), SDG2 (Zero Hunger), SDG3 (Good Health and Well-being), SDG12 (Responsible Consumption and Production), SDG13 (Climate Action), SDG14 (Life Below Water), and SDG15 (Life on Land) (Dicke 2018).

INSECT SPECIES PERMITTED FOR ANIMAL FEED

Currently, 11 insect species have been permitted as feed sources for farmed animals worldwide (Table 1), spanning 4 orders and 6 families. These include 4 species from Orthoptera (*A. domesticus*, *Gryllus assimilis* (Fabricius), *Gryllodes sigillatus* (Walker), *Teleogryllus emma* (Ohmachi & Matsuura)), 2 species from Diptera (*Musca domestica* Linnaeus, *H. illucens*), 1

Table 1. Insects species permitted as animal feed in the world.

Species	EU[z]	UK[y]	Canada[x]	USA[w]	China[v]	Taiwan[u]	Korea[t]	Japan[s]	African[r]
Orthoptera									
Gryllidae									
Acheta domesticus, house cricket	✓	✓							
Gryllus assimilis, jamaican field cricket	✓	✓							
Gryllodes sigillatus, tropical house cricket	✓	✓							
Teleogryllus emma, oriental garden cricket							✓		
Diptera									
Muscidae									
Musca domestica, common housefly	✓	✓						✓	
Stratiomyidae									
Hermetia illucens, black soldier fly (BSF)	✓	✓	✓	✓		✓	✓		✓
Hymenoptera									
Apidae									
Apis mellifera, western honey bee						✓			
Coleoptera									
Tenebrionidae									
Alphitobius diaperinus, lesser mealworm	✓	✓							
T. molitor, yellow mealworm (YML)	✓	✓			✓	✓	✓	✓	
Zophobas morio, superworm						✓			

Table 1. Insects species permitted as animal feed in the world. (continued)

Species	EU[z]	UK[y]	Canada[x]	USA[w]	China[v]	Taiwan[u]	Korea[t]	Japan[s]	African[r]
Lepidoptera									
Bombycidae									
Bombyx mori, domestic silk moth	✓				✓	✓		✓	

[z] Information collected from Jensen *et al*. (2021).

[y] Information collected from Tiwasing & Pate (2024).

[x] Information collected from Larouche *et al*. (2023) and NPC (2022).

[w] Information collected from Morrison Foerster (https://www.mofo.com/resources/insights/211028-alternative-protein-industry-series, visit on 3/27/2025). The Association of American Feed Control Officials (AAFCO) has approved BSF larvae for animal feed.

[v] Information collected from website of Ministry of Agriculture and Rural Affairs, People's Republic of China (http://www.moa.gov.cn/hd/zqyj/201203/P020120307371176222741.doc, visiting on 3/27/2025). Insects (including but not limited to silkworm pupa meal, defatted silkworm pupa, and mealworm meal) may be processed and incorporated into animal feed, provided they do not pose risks to public or animal health.

[u] Information collected from Lee *et al*. (2021).

[t] Information collected from website of Ministry of Agriculture, Food and Rural Affairs, Korean. (https://www.mafra.go.kr/home/5109/subview.do?enc=Zm5jdDF8QEB8JTJGYmJzJTJ-GaG9tZSUyRjc5MiUyRjU2MzkwNSUyRmFydGNsVmlldy5kbyUzRg%3D%3D, visiting on 3/27/2025).

[s] Information collected from website of Research Institute of Environment, Agriculture and Fisheries, Osaka Prefecture (https://www.knsk-osaka.jp/ibpf/guideline/, visiting on 3/27/2025)

[r] Information from Grabowski *et al*. (2020). Regulatory frameworks regarding the inclusion of insects in animal feed vary across countries, with many lacking specific guidelines on their use. In some countries, such as South Africa and Niger, the farming of black soldier flies for animal feed production is legally permitted.

species from Hymenoptera (*Apis mellifera* Linnaeus), 3 species from Coleoptera (*Alphitobius diaperinus* (Panzer)), *T. molitor*, *Zophobas morio* (Fabricius)), and 1 species from Lepidoptera (*Bombyx mori* Linnaeus).

Among these species, *T. molitor* is the second most widely approved specie after *H. illucens*, having been authorized in 6 countries or economic regions, including the EU, UK, China, Taiwan, South Korea, and Japan. Additionally, within the three approved species from the Tenebrionidae family, *T. molitor* has the broadest regulatory acceptance, underscoring its high industrial value and global recognition.

YM (*T. molitor*) CHARACTERISTICS

YM is one of the few insect species currently utilized in circular agriculture, animal feed, and high-value products. Taxonomically, it belongs to the class Insecta, order Coleoptera, and family Tenebrionidae. As a holometabolic insect, its life cycle includes 4 stages: egg (1–4 wk), larva (8–12 wk), pupa (1–4 wk), and adult (3–6 mo) (Fig. 1). YM primarily inhabits warm, humid, and dark environments, with optimal growth conditions at 25–28℃ and relative humidity (RH) of ≥ 70% (optimal RH range: 60–75%) (Barrett *et al*. 2023; Parsa *et al*. 2023). The eggs are glossy milky-white, approximately 1.2–1.4 mm in length. Newly hatched larvae are also milky-white but gradually turn yellowish-brown as they develop, undergoing 7–20 instars and reaching a final length of approximately 28–32 mm. Pupae are light yellowish-brown and measure around 15–17 mm, while adults are dark reddish-brown, ranging from 14–19 mm in length. Newly emerged adults exhibit a lighter coloration, are nocturnal, and lay eggs either individually or in clusters.

YM is believed to have originated from the Mediterranean region. However, it is now widely distributed due to the global transportation and trade of stored products (Moruzzo

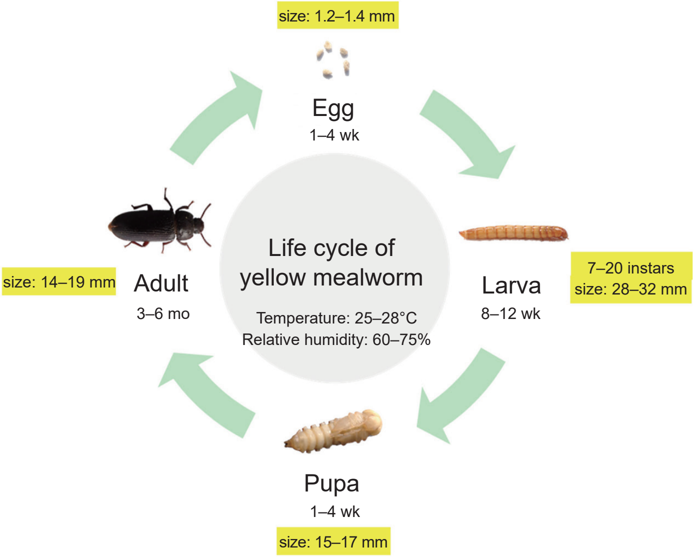

Fig. 1. Life history of *Tenebrio molitor*.

et al. 2021). It is classified as a secondary stored-product pest, capable of infesting flour, wheat bran, bread, and other processed cereal products, particularly under suboptimal storage conditions. However, improved global storage management has led to a significant decline in infestations in recent years.

Due to the high nutritional value of larvae and their adaptability to diverse feed substrates and rearing conditions (Bordiean *et al*. 2022), as well as their higher nutritional content compared to pupae and adults (Khanal *et al*. 2023), there have been approximately 300 billion yellow mealworm larvae (YML) reared annually worldwide as feed for amphibians, reptiles, and birds or processed into raw material for aquaculture, livestock feed (such as poultry, pigs, fish), and pet food. Additionally, YML has also been incorporated into circular agriculture systems and even human food production (Barrett *et al*. 2023). Currently, *T. molitor*, along with *A. diaperinus* and *A. domesticu*, is legally approved by the EU for use in animal feed, pet food, and human consumption (Commission Regulation (EU) 2017/893, 2017/2470, 2021/1372, 2022/188, 2023/58).

DEVELOPMENT OF YM APPLICATIONS IN CIRCULAR AGRICULTURE - LIMITED TO REARING ON AGRICULTURAL RESIDUE SUBSTRATES

Feasibility analysis based on rearing research cases, impacts of the feed nutritional composition

YML are highly adaptable to the decomposition of agricultural residues, making them one of the key insects of interest in circular agriculture (Nava *et al*. 2020). Numerous studies have explored the use of various agricultural production residues as rearing substrates for YML, including spent mushroom substrate (SMS), vegetable and fruit peels, olive pomace, rapeseed meal, sunflower seed meal, by-products of seed cleaning process of legumes (such as vetch, pea, lupin, lentil), beer yeast, cereal cultivation residues (such as rice straw, corn stalks), and cereal processing by-products (such as rice bran, rice husks, brewer's grain, black wheat, barley, durum wheat, oats, corn, triticale) (Kim *et al*. 2014; Ooincx *et al*. 2015; van Broekhoven *et al*. 2015; Li *et al*. 2020; Rumbos *et al*. 2021; Bordiean *et al*. 2022; Vrontaki *et al*. 2024).

Although YML can utilize a broad spectrum of agricultural residues, their adaptability and growth performance vary depending on substrate composition. Compared to BSF, YM primarily thrives on dry substrates, only requiring moisture from a few vegetables or fruit (such as market rejects) as supplementary sources. Suitable substrates for YM have a lower moisture content, whereas BSF larvae grow better on agricultural residues with moisture content above 60% (Kröncke & Benning 2022; Barrett *et al*. 2023), making them more suitable for semi-solid to liquid substrates.

Current studies indicate that although YM can digest various agricultural residues, their growth performance remains suboptimal compared to traditional rearing substrates such as wheat bran and carrots. Fully replacing traditional substrates with plant-based agricultural residues has proven challenging. Cereal processing by-products, however, show potential to entirely replace wheat bran as a rearing substrate for YML. Despite this, YML reared on cereal by-products show slightly lower survival rates, larval weight, and pre-adult development time compared to those reared on wheat bran (Oonincx *et al*. 2015; van Broekhoven *et al*. 2015; Rumbos *et al*. 2021). Other agricultural residues are unlikely to serve as a complete substitute for wheat bran.

For homeothermic animals, total feed energy content directly impacts growth rate and efficiency, but as poikilothermic animals, YM does not expend additional energy to maintain body temperature, making the nutritional composition of the feed more important than its total caloric content. Protein content plays a crucial role in the development and survival of YML. Low-protein diets are associated with reduced larval survival and prolonged developmental periods, whereas high-protein diets accelerate development, enhance feeding activity, and promote larval weight gain. (Oonincx *et al*. 2015; van Broekhoven *et al*. 2015). However, the relationship between protein content and larval growth is not always linear, and other nutritional factors (such as fat, amino acids, vitamins, and minerals) also play the roles (Rumbos *et al*. 2021). Additionally, as a stored-product pest, growth of YML remains dependent on carbohydrate-rich substrates like cereals. Therefore, when developing alternative diets, careful consideration must be given to their nutritional composition, ensuring an optimal carbohydrate-to-protein ratio to mitigate risks of malnutrition, suboptimal growth, and potential cannibalism among larvae.

In addition to adjusting the nutritional composition of the rearing substrate, it is also important to note that different insect species have varying abilities to adapt to feed substrates. Some researchers propose a staged decomposition approach, utilizing different insect species for processing agricultural residues. Wang *et al*. (2017) found that corn stalks pre-degraded by YML are better suited for consumption by BSF larvae, leading to higher biomass production. This approach could also be extended to agricultural residues that are less suitable for YML rearing, thereby improving their utilization feasibility and enhancing the overall bioconversion efficiency of these waste materials.

Advantages based on rearing costs and avoidance of animal diseases

With the increasing commercialization and large-scale production of YML, breeding costs have become a key issue for enterprises worldwide. Traditional YML farming primarily depends on wheat bran as a carbohydrate source, supplemented with vegetables such as carrots, cabbage, or potatoes for moisture. However, these feed substrates are also human food, raising concerns that the production of YML as an alternative protein source may intensify the competition for food between humans, livestock, and pets. Therefore, identifying suitable alternative feed substrates to replace conventional feed formulations has become a critical research focus.

Agricultural residues generated during crop cultivation or processing offer a potential solution to the problem of food competition and reduce breeding costs associated with large-scale YML farming. By incorporating locally sourced agricultural by-products into YML feed formulations, can effectively lower production costs while facilitating the processing and utilization of agricultural wastes, leading to a decrease in market product prices, increased competitiveness, and improved economic feasibility.

Additionally, insects lack genes encoding prion proteins, which are responsible for transmissible spongiform encephalopathy (TSE) in herbivorous animals (Gałęcki *et al*. 2023). If insects are fed with plant-based substrates, the risk of spreading animal diseases can be effectively avoided, ensuring the safety and reliability of YML as ingredients in the animal feed and pet food.

Most importantly, this strategy facilitates the integration of YML into the circular economy model, enabling the continuous recycling and efficient utilization of agricultural resources. This further reinforces the role of YML in circular agriculture, contributing to the realization of sustainable development goals.

Important issues to be considered in rearing YML: Pesticide, heavy metal, and toxic residue contamination

Previous studies have demonstrated that YML can utilize a broad range of feed substrates, as well as possessing the capacity of degrading and metabolizing certain toxic compounds (Siddiqui *et al*. 2024). However, the potential presence of harmful contaminants- such as pesticides, heavy metals, plastic microparticles, pathogenic microorganisms, and mycotoxins- must be investigated in plant-based substrates used for feed. It is essential to prevent these substances from entering the food chain through insect biomass.

Houbraken *et al*. (2016) reported that pesticides can accumulate in YML bodies through feeding on contaminated substrates, particularly those with high n-octanol-water partition coefficients (Kow), which are readily absorbed and bioaccumulated in insects. Mlček *et al*. (2017) investigated the accumulation of heavy metals (Pb, Cd, Cu, Zn) in YML exposed to contaminated feed substrates and found that YML exhibited a higher absorption and retention capacity for copper (Cu) and zinc (Zn). Additionally, if the feed substrate contains materials with incomplete removal of plastic packaging, residual microplastics such as polyethylene (PE), polypropylene (PP), or polyvinyl chloride (PVC) may persist and accumulate in the YML, potentially leading to stunted growth and reduced survival rates (Peng *et al*. 2023).

During storage, agricultural residues may serve as reservoirs for harmful microorganisms (such as bacteria: *Salmonella* spp., *Listeria* spp., enteropathogenic *Escherichia coli* (Migula), *Clostridium perfringens* (Veillon & Zuber)), as well as mycotoxins (such as aflatoxin, vomitoxin, fumonisins, zearalenone, ochratoxin, T-2 toxin). Yet, studies have shown that YML can metabolize ingested aflatoxin B1 and zearalenone into less toxic derivatives or excrete them directly. Implementing a fasting period of at least one day prior to harvest can further reduce residual toxin levels, ensuring compliance with safety standards (Bosch *et al*. 2017; Niermans *et al*. 2019; Zhao *et al*. 2022). Still, some mycotoxins, such as T-2 and HT-2 toxins produced by *Fusarium* spp. in contaminated grains, may be accumulated in YML tissues (Piacenza *et al*. 2021), that raises the concerns regarding their suitability as feed ingredients for livestock farming and aquaculture.

Beyond pollutant residues, certain plants naturally contain antinutritional factors or alkaloids such as saponins, may adversely affect insect growth and development, thereby influencing the safety and efficacy of YML as an ingredient in animal feed and pet food (Schrögel & Wätjen 2019). Therefore, rigorous evaluation of agricultural residues used as feed substrates for YML rearing is essential to ensure the absence of hazardous contaminants, verify non-toxicity to the larvae, and establish a reliable and sustainable supply chain. Meeting these criteria is crucial to ensure the use of YML reared on agricultural by-products as a cost-effective and stable protein source. This approach not only enhances their application in the animal feed and pet food industries but also reinforces circular economy principles that support sustainable production systems.

DEVELOPMENT OF YM APPLICATIONS IN LIVESTOCK FARMING INCLUDING POULTRY, LIVESTOCK, AND AQUATIC ANIMALS

Nutritional value of YML

YML is composed of crude protein (37.3–76.2%), crude fat (6.1–58.2%), crude fiber (3.5–38.8%), and ash (2.6–8.1%) on a dry matter (DM) basis (Table 2), with substantial variation influenced by the rearing substrate and environmental conditions. The crude protein content of YML is comparable to that of house crickets and fishmeal, and significantly exceeds that of BSF larvae and soybean meal. Similarly, crude fat and crude fiber contents in YML exceed those in house crickets, BSF larvae, soybean meal, and fishmeal, further reinforcing their potential as a high-quality alternative protein source for animal feed.

YML are rich in various amino acids (Table 3), particularly glutamic acid (Glu, 2.08–12.26% DM), leucine (Leu, 1.39–10.90% DM), lysine (Lys, 1.20–10.56% DM), and alanine (Ala, 2.48–10.09% DM). Other notable amino acids include proline (Pro, 1.60–9.59% DM), asparagine (Asn, 1.54–8.51% DM), phenylalanine (Phe, 1.20–8.20% DM), tyrosine (Tyr, 2.15–8.15% DM), valine (Val, 1.89–7.61% DM), and threonine (Thr, 1.20–7.50% DM), whereas cysteine (Cys, 0.35–3.16% DM) and methionine (Met, 0.52–2.52% DM) are present in lower concentrations. Compared to soybean meal, fishmeal, and other insect species, YML

Table 2. Main constituents (%) of *Tenebrio molitor* compared to other protein sources.

Main constituents	*Acheta domesticus*[z] House cricket	*Hermetia illucens*[y] Black soldier fly larvae (BSF)	*T. molitor*[x] Yellow mealworm larvae (YML)	Soybean meal[w]	Fish meal[v]
Dry matter (DM)	21.1–47.7	21.9–98.9	31.1–99.0	86.9–92.8	92.1
Crude protein (CP, %DM)	15.4–76.2	27.5–65.5	37.3–76.2	41.8–50.0	65.3–72.3
Crude fat (CF, %DM)	3.3–43.9	4.6–51.5	6.1–58.2	0.8–1.4	10.0–10.4
Crude fiber (CF, %DM)	3.7–10.2	4.1–23.2	3.5–38.8	3.4–7.9	0.3–0.8
Ash (%DM)	3.0–11.5	2.7–19.7	2.6–8.1	5.6–7.9	17.2
Chitin (%DM)	6.1–8.3	3.9–6.7	4.3–8.9	NR[u]	NR

[z] Data compiled from Pilco-Romero *et al*. (2023), Ververis *et al*. (2022), Magara *et al*. (2021), Udomsil *et al*. (2019) and Nogales-Mérida *et al*. (2019).
[y] Data compiled from Vasilopoulos *et al*. (2024), Lu *et al*. (2022), Zulkifli *et al*. (2022), Abd El-Hack *et al*. (2020) and Nogales-Mérida *et al*. (2019).
[x] Data compiled from Vasilopoulos *et al*. (2024), Syahrulawal *et al*. 2023, Shafique *et al*. (2021), Hong *et al*. (2020) and Nogales-Mérida *et al*. (2019).
[w] Data compiled from Lu *et al*. (2022), Abd El-Hack *et al*. (2020), Ibáñez *et al*. (2020), Lagos & Stein (2017) and Hussein *et al*. (2017).
[v] Data compiled from Lu *et al*. (2022), Abd El-Hack *et al*. (2020) and Hussein *et al*. (2017).
[u] NR: not reported.

Table 3. The amino acid compositions of *Tenebrio molitor* compared to other protein sources.

Amino acids (%DM[z])	*Acheta domesticus*[y] House cricket	*Hermetia illucens*[x] Black soldier fly larvae (BSF)	*T. molitor*[w] Yellow mealworm larvae (YML)	Soybean meal[v]	Fish meal[u]
Essential amino acid (EAA)					
Arginine (Arg)[t]	3.92–6.10	1.73–6.20	1.80–6.14	2.30–3.60	2.85–4.20
Cysteine (Cys)	0.40–0.80	0.01–1.38	0.35–3.16	0.60–0.80	0.38–0.70
Histidine (His)	1.32–2.25	0.77–3.25	0.84–4.44	1.25–1.41	0.92–1.50
Isoleucine (Ile)	0.04–4.45	0.13–4.80	1.07–6.48	1.00–2.50	1.63–3.20
Leucine (Leu)	0.07–9.75	0.19–7.83	1.39–10.90	3.33–3.90	2.95–4.80
Lysine (Lys)	0.05–5.40	0.15–7.40	1.20–10.56	1.00–3.12	2.27–5.50
Methionine (Met)	0.01–1.40	0.05–3.72	0.52–2.52	0.60–0.70	0.44–2.20
Phenylalanine (Phe)	0.03–3.00	0.07–7.76	1.20–8.20	2.20–2.60	1.99–2.60
Threonine (Thr)	0.74–3.60	0.20–4.50	1.20–7.50	1.10–2.60	1.51–3.10
Tryptophan (Trp)	0.13–0.55	0.02–0.70	0.02–5.80	0.65–1.20	0.39–0.70
Tyrosine (Tyr)	1.00–4.44	1.71–6.71	2.15–8.15	1.49–1.90	1.42–2.00
Valine (Val)	0.05–4.50	0.03–6.79	1.89–7.61	1.60–2.40	1.72–3.90
Non-essential amino acid (non-EAA)					
Alanine (Ala)	3.67–8.85	1.40–8.21	2.48–10.09	1.84–2.20	1.90–4.20
Asparagine (Asn)	NR[z]	NR	1.54–8.51	NR	NR
Aspartate (Asp)	4.73–7.75	3.22–5.28	3.07–4.89	4.82–5.50	4.63–5.80
Asparagine (Asn) + Aspartate (Asp)	4.61	NR	0.50–9.74	NR	NR
Glutamate (Glu)	6.87–10.45	0.85–6.37	2.08–12.26	7.40–8.90	8.14–8.40
Glutamine (Gln)	NR	NR	NR	NR	NR
Glutamate (Glu) + Glutamine (Gln)	6.45	3.84–13.10	3.80–12.53	NR	NR
Glycine (Gly)	1.04–4.27	0.12–6.15	1.30–6.60	1.81–4.30	1.73–5.00
Proline (Pro)	1.15–4.31	2.14–6.68	1.60–9.59	2.07–2.80	2.21–3.10
Serine (Ser)	1.02–3.02	1.50–4.88	1.36–6.60	1.93–2.40	2.07–2.60

[z] DM: dry matter; NR: not reported.

[y] Data compiled from Pilco-Romero *et al*. (2023), Magara *et al*. (2021), Udomsil *et al*. (2019) and Nogales-Mérida *et al*. (2019).

[x] Data compiled from Vasilopoulos *et al*. (2024), Lu *et al*. (2022), Zulkifli *et al*. (2022), Abd El-Hack *et al*. (2020) and Nogales-Mérida *et al*. (2019).

[w] Data compiled from Vasilopoulos *et al*. (2024), Syahrulawal *et al*. 2023, Shafique *et al*. (2021), Hong *et al*. (2020) and Nogales-Mérida *et al*. (2019).

[v] Data compiled from Lu *et al*. (2022), Abd El-Hack *et al*. (2020), Lagos & Stein (2017) and Hussein *et al*. (2017).

[u] Data compiled from Lu *et al*. (2022), Abd El-Hack *et al*. (2020) and Hussein *et al*. (2017).

[t] Arg is not essential for most animals, it is considered essential for birds and certain mammals (cats and ferrets).

contain higher levels of most amino acids, except for methionine and aspartic acid. Notably, YML are a rare source of asparagine, an absent amino acid in soybean meal, fishmeal, house crickets, and BSF larvae. In addition to supplying all 11 essential amino acids (EAAs) required by animals, YML also provide arginine (Arg), an EAA for birds and certain mammals (cats and ferrets). The EAAs in YML have been shown to enhance meat quality and feed efficiency in farmed animals (Hou & Wu 2018; An *et al*. 2025). The substantial presence of non-essential amino acids (NEAAs) in YML further reduce the metabolic energy required for protein synthesis in animals, thereby improving feed efficiency and reinforcing the suitability of YML as a sustainable protein source.

YML are rich in unsaturated fatty acids (UFAs) (Table 4), with monounsaturated fatty acids (MUFAs) being the most predominant, accounting for 8.01–59.39% DM. Oleic acid (C18:1n9) is the principal MUFA, comprising 3.55–57.63% DM. The polyunsaturated fatty acid (PUFA) content in YML ranges from 7.24–33.70% DM, with linoleic acid (C18:2n6) being the predominant PUFAs (8.01–35.58% DM). However, YML contain relatively low levels of omega-3 (n-3) fatty acids (0.11–1.80%, DM), resulting in a higher n-6/n-3 ratio (0.69–71.42). The saturated fatty acid (SFA) contents in YML are lower than those of BSF larvae, but comparable to t those of house crickets, with values ranging from 4.94% to 35.40% of DM. Among SFAs, palmitic acid (C16:0) is the most abundant component, followed by stearic acid (C18:0), pentadecylic acid (C15:0), and myristic acid (C14:0). Notably, YML lack lauric acid (C12:0), a fatty acid that is abundant in BSF larvae and recognized for its antimicrobial properties While YML have a high UFA content, their low omega-3 levels and elevated n-6/n-3 ratio limit their suitability in animal feed (Oonincx *et al*. 2015). Therefore, while YML serve as a viable protein source for livestock, their application in animal feed remains suboptimal unless dietary modifications are implemented to optimize their fatty acid profile.

The mineral composition of YML is presented in Table 5. Potassium (K) (3,737–19,290 mg kg^{-1} DM), magnesium (Mg) (200–16,300 mg kg^{-1} DM), and phosphorus (P) (700–14,290 mg kg^{-1} DM) are the predominant minerals, followed by calcium (Ca) (168–5,000 mg kg^{-1} DM) and sodium (Na) (404–3,644 mg kg^{-1} DM). Compared to house crickets and BSF larvae, YML contain higher P and Mg but lower Ca and Na than BSF larvae. Relative to soybean meal and fishmeal, YML exhibit comparable P and Mg levels but lower Ca and Na levels. Additionally, YML contain trace amounts of heavy metals, including manganese (Mn), Zn, Cu, and iron (Fe), with concentrations below 200 mg kg^{-1} (DM). These levels are comparable to those found in house crickets, soybean meal, and fishmeal. In contrast, BSF larvae tend to bioaccumulate higher concentration of heavy metals from food substrates. Studies indicate that BSF larvae can bioaccumulate Mn, Zn, Cu, and Fe at levels reaching 166, 103, 10.7, and 191 g kg^{-1} (DM), respectively, substantially higher than those found in YML, house crickets, soybean meal, and fishmeal. However, this does not imply that YML are entirely devoid of the risk of heavy metal accumulation. Bednarska & Świątek (2016) demonstrated that when YML were fed with Cd-containing flour, the concentration of cadmium (Cd) in their tissues increased with the amount consumed and the duration of exposure, indicating a potential risk of heavy metal accumulation. Overall, YML serve as a valuable source of minerals and can effectively replace soybean meal as a mineral supplement in animal feed. However, additional Ca and P supplementation should be considered when replacing fishmeal.

In addition to their major nutrients, YML contain bioactive compounds that may contribute to animal health, including vitamins (B12, B3, B2, B5, B7, E, and H) and bioactive substances such as antimicrobial peptides (AMPs), polysaccharides, and β-glucanase (Moruzzo *et al*. 2021; Syahrulawal *et al*. 2023). AMPs, including α-helix peptides, defensins, and

Table 4. The fatty acid compositions of *Tenebrio molitor* compared to other protein sources.

Fatty acids (%DM[z])	*Acheta domesticus*[y] House cricket	*Hermetia illucens*[x] Black soldier fly larvae (BSF)	*T. molitor*[w] Yellow mealworm larvae (YML)
Saturated fatty acid (SFA)	3.14–32.36	36.20–81.81	4.94–35.40
C_{10}:0, Capric acid	0.01	0.00–2.03	NR[z]
C_{12}:0, Lauric acid	0.02–0.27	7.5–65.1	0.01–0.38
C_{14}:0, Myristic acid	0.04–1.65	5.00–11.77	0.20–5.21
C_{14}:1n5, Myristoleic acid	0.02–0.44	NR	NR
C_{15}:0, Pentadecylic acid	0.01–0.11	0.13–14.38	0.06–7.10
C_{16}:0, Palmitic acid	1.56–24.81	1.03–24.59	3.43–23.60
C_{17}:0, Margaric acid	0.02–0.12	NR	NR
C_{17}:1, Civetic acid	0.24	NR	NR
C_{18}:0, Stearic acid	0.58–8.54	0.98–6.90	0.07–7.92
C_{20}:0, Arachidic acid	0.00–0.13	NR	NR
C_{21}:0, Heneicosylic acid	0.01–0.24	0.00–0.82	NR
C_{22}:0, Behenic acid	0.06	0.00–0.26	NR
C_{23}:0, Tricosylic acid	0.02	NR	NR
C_{24}:0, Lignoceric acid	0.02	NR	NR
Unsaturated fatty acid (UFA)			
Monounsaturated fatty acid (MUFA)	4.14–33.02	8.55–29.00	8.01–59.39
C_{16}:1n7, Palmitoleic acid	0.09–2.79	0.80–7.60	0.11–2.90
C_{18}:1n7, cis-Vaccenic acid	NR	0.12–0.43	NR
C_{18}:1n9, Oleic acid	1.54–30.23	5.66–22.70	3.55–57.63
C_{18}:1n9t, Elaidic acid	0.03	NR	NR
C_{20}:1n9, Gondoic acid	0.01–0.02	0.00–0.46	0.02–0.39
C_{22}:1n9, Erucic acid	0.01–0.52	NR	1.62
Polyunsaturated fatty acid (PUFA)	1.36–34.29	5.87–42.28	7.24–33.70
C_{18}:2n6, Linoleic acid	0.06–41.39	3.80–31.40	8.01–35.58
C_{18}:3n3, α-Linolenic acid	0.01–1.74	0.00–3.60	0.01–2.27
C_{18}:3n6, γ-Linolenic acid	0.01	NR	0.03–1.85
C_{18}:4n3, Stearidonic acid	NR	0.05–0.87	NR

Table 4. The fatty acid compositions of *Tenebrio molitor* compared to other protein sources. (continued)

Fatty acids (%DM[z])	*Acheta domesticus*[y] House cricket	*Hermetia illucens*[x] Black soldier fly larvae (BSF)	*T. molitor*[w] Yellow mealworm larvae (YML)
C_{20}:2n6, Dihomolinoleic acid	0.19	0.00–0.38	NR
C_{20}:3n3, Dihomo-α-linolenic acid	0.01	NR	NR
C_{20}:3n6, Dihomo-γ-linolenic acid	0.01	0.00–0.38	NR
C_{20}:4n6, Arachidonic acid	0.01	0.10–0.29	0.04–0.50
C_{20}:5n3, Timnodonic acid (EPA)	0.06–0.75	0.01–3.50	0.00–0.21
C_{22}:4n6, Adrenic acid	NR	0.10–0.29	0.13–0.46
C_{22}:5, Docosapentaenoic acid (DPA)	0.01–0.06	0.00–3.50	NR
C_{22}:6n3, Cervonic Acid (DHA)	NR	0.01–1.70	0.04–0.24
Omega-3 (n-3)	0.07–2.49	0.10–6.20	0.11–1.80
Omega-6 (n-6)	1.05–31.80	4.52–40.29	6.97–32.62
n-6/n-3	2.00–40.90	0.95–100.00	0.69–71.42

[z] DM: dry matter; NR: not reported.

[y] Data compiled from Pilco-Romero *et al*. (2023), Magara *et al*. (2021), Udomsil *et al*. (2019), and Nogales-Mérida *et al*. (2019).

[x] Data compiled from Vasilopoulos *et al*. (2024), Lu *et al*. (2022), Zulkifli *et al*. (2022), and Nogales-Mérida *et al*. (2019).

[w] Data compiled from Vasilopoulos *et al*. (2024), Shafique *et al*. (2021), Hong *et al*. (2020), and Nogales-Mérida *et al*. (2019).

Table 5. The mineral compositions of *Tenebrio molitor* compared to other protein sources.

Minerals (mg kg^{-1} DM^{z})	*Acheta domesticus*[y] House cricket	*Hermetia illucens*[x] Black soldier fly larvae (BSF)	*T. molitor*[w] Yellow mealworm larvae (YML)	Soybean meal[v]	Fish meal[u]
Calcium (Ca)	275–3,150	1,200–45,150	168–5,000	1,600–4,660	55,500
Phosphorus (P)	2,250–10,389	1,000–11,500	700–14,290	5,640–7,660	31,300
Magnesium (Mg)	226–1,366	1,000–6,200	200–16,300	310–4,940	1,700
Potassium (K)	1,260–12,800	1,700–21,300	3,737–19,290	20,200–25,200	7,100
Sodium (Na)	950–8,633	600–15,600	404–3,644	60–1,090	7,100
Sulfur (S)	1	100–270	NR[z]	NR	NR
Manganese (Mn)[t]	9–44	134–166,000	3–19	30–71	36
Zinc (Zn)[t]	22–240	70–103,000	1–184	28–77	160
Copper (Cu)[t]	5–51	10–10,700	1–65	9–19	12
Iron (Fe)[t]	19–112	70–191,000	1–184	90–919	478
Selenium (Se)	1–6	NR	NR	NR	NR
Molybdenum (Mo)	0–635	NR	NR	NR	NR

[z] DM: dry matter; NR: not reported.

[y] Data compiled from Pilco-Romero *et al*. (2023), Ververis *et al*. (2022), Magara *et al*. (2021) and Udomsil *et al*. (2019).

[x] Data compiled from Vasilopoulos *et al*. (2024), Lu *et al*. (2022), and Zulkifli *et al*. (2022).

[w] Data compiled from Vasilopoulos *et al*. (2024), Syahrulawal *et al*. 2023, Shafique *et al*. (2021) and Hong *et al*. (2020).

[v] Data compiled from Ibáñez *et al*. (2020) and Hussein *et al*. (2017).

[u] Data compiled from Hussein *et al*. (2017).

[t] Belongs to heavy metals.

attacins, exhibit strong antimicrobial properties, capable of inhibiting the growth of various pathogens. Polysaccharides, such as chitin (4.3–8.9% DM) and chitosan, found in YML, have demonstrated antibacterial activity against bacteria such as *E. coli* and *S. enterica*. These bioactive compounds can enhance immune function, improve disease resistance, and support overall health, providing additional benefits in livestock nutrition and reducing the need for antibiotics (Elahi *et al*. 2022; Chen *et al*. 2023; Syahrulawal *et al*. 2023).

Case studies on the impact of YML on livestock growth performance

In recent years (2019–2024), several studies have explored the potential of using YML as alternative protein source in various farmed animals, including aquatic species such as red sea bream (*Pagrus major* (Temminck & Schlegel)) (Ido *et al*. 2019), largemouth bass (*Micropterus salmoides* (Lacepède)) (Chen *et al*. 2023), yellowtail (*Seriola quinqueradiata* Temminck & Schlegel) (Ido *et al*. 2024), giant river catfish (*Pangasianodon hypophthalmus* (Sauvage)) (Ardra *et al*. 2025), giant freshwater prawn (*Macrobrachium rosenbergii* (De Man)) (Chong *et al*. 2022), Chinese mitten crab (*Eriocheir sinensis* H. Milne Edwards) (Yao *et al*. 2024), as well as terrestrial farmed animals such as broiler chickens (Elahi *et al*. 2020), Japanese quail (*Coturnix japonica* Temminck & Schlegel) (Dalle Zotte *et al*. 2024), weaned pigs ((Yorkshire × Landrace) × Duroc) (Ao *et al*. 2020; Malla *et al*. 2024), steers (Carrasco & Drewery 2024), and rabbits (Volek *et al*. 2021). These studies investigated the feasibility of replacing fishmeal with live YML, whole-fat, or defatted YML powder, partially or completely, in animal feed. The evaluations primarily focused on growth performance, feed intake, digestibility, meat quality, and blood health indices (Table 6).

Balancing the nutritional composition of feeds is crucial for optimal growth and health in animals. Research has shown that maintaining the proper nutritional balance allows for the replacement of fishmeal with whole-fat or defatted

Table 6. Effects of *Tenebrio molitor* as animal feed on growth and physiological performance of farmed animals.

Farmed animals	YML^z form	YML ratio in diets	Effects (compared to general diet)	References
Terrestrial animal				
Broiler chicks	Dried meal	4%	Increase in body weight and average daily gain during the starter phase.	Elahi *et al*. (2020)
	Fresh meal	10.48%	Decrease in animal hematological characteristics (decrease lysozyme concentration) and abdominal fat.	Elahi *et al*. (2020)
Coturnix japonica	Live	10%	Increase in feed intake but decrease in egg overall flavor.	Dalle Zotte *et al*. (2024)
(Yorkshire × Landrace) × Duroc	Dried meal	2%	Similar growth performance, apparent total tract digestibility of nutrients, blood profiles or fecal noxious gas emission.	Ao *et al*. (2020)
	Defatted dried meal	7.66%	Similar in growth performance and most gut health parameters, with an increase in the protection of the intestinal mucosa barrier function (reduce plasma diamine oxidase).	Malla *et al*. (2024)
Fattening rabbits	No mention	3%	Similar in the coefficients of total tract apparent digestibility and nitrogen output, despite a decrease in feed intake and body weight.	Volek *et al*. (2021)
Steers	Dried meal	Supplements (Isonitrogenous)	Stimulation in forage utilization (increase forage intake, total organic matter).	Carrasco & Drewery (2024)

Table 6. Effects of *Tenebrio molitor* as animal feed on growth and physiological performance of farmed animals. (continued)

Farmed animals	YML^z form	YML ratio in diets	Effects (compared to general diet)	References
Aquatic animal				
Pagrus major	Defatted dried meal	65% (100% replacement of fish meal)	Increase in body weight gain rate.	Ido *et al*. (2019)
	Defatted dried meal	5–10%	Increase in survival rate after infection with *Edwardisella tarda*.	Ido *et al*. (2019)
Micropterus salmoides	Dried meal	5.28–10.56% (Isonitrogenous and isolipidic, 12–24% replacement of fish meal)	Increase in growth performance (final body weight, weight gain rate, specific growth rate), antioxidant capacity and immunity (enhance liver health).	Chen *et al*. (2023)
	Dried meal	15.58–21.23% (Isonitrogenous and isolipidic, 36–48% replacement of fish meal)	Decrease in growth performance and liver health.	Chen *et al*. (2023)
Seriola quinqueradiata	Full-fat dried meal	18.9% (Isonitrogenous and isolipidic)	Similar in growth performance.	Ido *et al*. (2024)
	Full-fat dried meal	10–20% (Isonitrogenous, not isolipidic)	Decrease in fork length and body weight.	Ido *et al*. (2024)
Pangasianodon hypophthalmus	Defatted dried meal	3.75–7.5% (Isonitrogenous and isolipidic, 7.07–14.14% replacement of fish meal)	Similar in the growth performance, whole body proximate composition, haematological and serum indices.	Ardra *et al*. (2025)
Eriocheir sinensis	Defatted dried meal	5.4–16.3% (Isonitrogenous and isolipidic, 25–75% replacement of fish meal)	Similar in the growth performance, intestinal health, serum immune, and antioxidant indexes.	Yao *et al*. (2024)
Macrobrachium rosenbergii	Live	Each treatment was fed GFP^z twice a day (9 am and 4 pm) until visibly full	Although no significant differences were observed, the feed conversion ratio of the live mealworm feeding group (1.66) was higher than that of the other two groups (commercial feed (1.76); and a 50/50 formula of commercial feed and live mealworms (1.72)).	Chong *et al*. (2022)

^{z}YML: yellow mealworm larvae; GFP: giant freshwater prawn.

dried YML powder, which not only promotes growth performance but also enhances animal health due to the bioactive compounds present in YML. However, when the replacement ratio of YML powder is too high or the feed's nutritional composition becomes unbalanced, the positive substitution effect may be significantly reduced. Ido *et al*. (2024) found that replacing 10% and 20% of the fishmeal with YML powder in feeds led to decreased body length and weight in yellowtail (*S. quinqueradiata*) as the replacement ratio increased. Chen *et al*. (2023) observed that when the replacement ratio of YML powder exceeded 36%, growth performance of largemouth bass (*M. salmoides*) significantly declined. Yao *et al*. (2024) reported that completely replacing fishmeal with defatted YML powder negatively impacted growth, serum immunity, and antioxidant indices in Chinese mitten crab (*E. sinensis*). A similar trend was observed in terrestrial farmed animals. Elahi *et al*. (2020) found that adding 10.48% fresh YML slurry to the diet reduced abdominal fat content in broiler chickens, while Volek *et al*. (2021) observed that adding 3% YML to the diet resulted in reduced feed intake and weight gain in rabbits.

The negative impact on growth and health may be attributed to several factors, including the excessive intake of chitin, a type of fiber found in YML. While many animals possess intestinal enzymes, such as chitinase, to break down chitin, excessive chitin intake can result in incomplete digestion. This can lead to the formation of indigestible complexes when chitin binds with amino acids, thereby interfering with digestion and absorption, which can stunt animal growth (Chen *et al*. 2023). Additionally, an imbalance in the fatty acid composition of the feed can adversely affect animal growth and health. For instance, a deficiency in omega-3 fatty acids can slow the growth of fish fry, while an excess of PUFAs may negatively impact the blood characteristics of broiler chickens (Elahi *et al*. 2020; Ido *et al*. 2024).

In conclusion, partial replacement of fishmeal with YML powder in animal feeds is a feasible approach. However, the replacement ratio must be carefully adjusted based on factors such as the species of farmed animals, feed freshness, and overall nutritional composition. Furthermore, the current market lacks large-scale production and a stable supply of YML powder, which presents challenges in accurately assessing its metabolizable energy and nutritional utilization efficiency. Therefore, further research is required to enhance the technology for large-scale application of YML powder in animal feeds, ensuring its feasibility and effectiveness in practical settings (Lee *et al*. 2024).

HIGH-VALUE APPLICATIONS OF YM ACROSS VARIOUS INDUSTRIES

With the UN-SDGs, large-scale insect farming is increasingly becoming a strategic industry in many countries, with the YML (*T. molitor*) and BSF (*H. illucens*) emerging as key representative species. YML has been widely incorporated into human food, pet food, and snacks (Ribeiro *et al*. 2018). Although insect-based proteins offer environmental, health, and nutritional benefits, their widespread acceptance remains limited. Therefore, exploring the development of economically valuable products derived from insects and their by-products such as medical materials, industrial raw materials, bioenergy, and aviation fuel, is considered a practical strategy to support the early-stage economics of insect farming. Owing to interdisciplinary advancements in industrial, biomedical, and food sciences, academic research, patents, and commercial applications related to such uses have steadily increased, demonstrating the feasibility of utilizing YML biomass as a high-value raw material. Given the substantial body of research and industrial investment already focused on YML as ingredients in human and pet food, these applications are excluded from present review. Instead, the following sections focus on diversified applications of high-quality products derived from YML reared on plant-based substrates, including agricultural residues or by-products. These applications include commercialized products, prototypes under development, and innovations with promising future potential. Their viability depends on whether technological advancements can meet practical or economic thresholds. The objective of this section is to provide stakeholders including policymakers, circular agriculture practitioners, insect farmers, and potential industry adopters with a sustainable model that balances environmental and economic benefits. In doing so, insect farming may evolve into a green industry that contributes to food security, enhances human and animal nutrition, reduces carbon emissions, and minimizes waste, paving the way for long-term sustainability.

Animal husbandry and aquaculture

Feed additives are essential components in animal nutrition, formulated to promote health, enhance growth performance, and improve feed efficiency. The incorporation of insect meal into animal diets has been shown to prevent and treat diseases, stimulate growth, and enrich animal products with bioactive compounds. Studies have demonstrated that incorporating appropriate proportions of insect meal into the diets of farmed animals has minimal impact on the physicochemical or sensory properties of the resulting meat. However, notable alterations in the fatty acid profile have been observed (Bingqian *et al*. 2023). The effects of mealworm-based feed applications in both animal husbandry and aquaculture are summarized in Table 6.

Beyond its nutritional benefits, insect meal has shown promising potential as an alternative to antibiotics, whose overuse in animal production has raised global concerns due to the emergence of antibiotic-resistant bacteria and residual contamination in animal products, groundwater, soil, and feed. In response to these risks, EU implemented a ban in 2006 on the use of antibiotics as growth promoters in animal feed (Ghimpețeanu *et al*. 2022), that facilitates the search for viable substitutes. One promising substitute is YML meal, which has demonstrated beneficial effects on animal health and productivity. Islam & Yang (2017) reported that incorporating probiotics-fermented YML powder into broiler chick diets reduced the FCR, mortality rates, and concentrations of *E. coli* and *Salmonella* spp. in the cecum. Similarly, Ido *et al*. (2019) demonstrated that supplementing fish feed with 5–10% defatted YML powder significantly improved the survival rate of *P. major* infected with *Edwardsiella tarda* Ewing & McWhorter, a common fish pathogen. In parallel, Malla *et al*. (2024) showed that the inclusion of 7.66% defatted YML powder in weaned pig diets lowered plasma diamine oxidase levels, thereby enhancing mucosal barrier function and improving gut health. Collectively, these findings highlight the potential of YML meal as a functional feed ingredient that supports animal health, enhances performance, and reduces reliance on conventional antibiotics.

Biological control industry

YM can be mass-reared efficiently and provide stable yields at relatively low costs compared to natural hosts of many agriculturally important pests, making them ideal alternative hosts for the mass production of natural enemies used in biological control programs. Previous studies have identified their pupae as effective alternate hosts for parasitoids targeting a wide range of Lepidopteran pests, including species from the families Arctiidae, Geometridae, Oecophoridae, Pyralidae, Riodinidae, and Nymphalidae (Zanuncio *et al*. 2008; Favero *et al*. 2013; Li *et al*. 2019; Machado *et al*. 2023). Particularly, Li *et al*. (2019) reported that 1- to 2-day-old YM pupae are highly suitable as substitute hosts for *Chouioia cunea* Yang, a parasitoid used in the biological control of the fall webworm (*Hyphantria cunea* (Drury)). Rearing costs using YM pupae were significantly lower than those of the conventional host Chinese tussah (*Antheraea pernyi* Guérin-Méneville). Additionally, YML powder has also been used as a nutrient medium for culturing entomopathogenic nematodes

(Widiyaningrum *et al*. 2020). Given their role as alternate hosts for numerous natural enemies of crop pests, YM are frequently used in field experiments to monitor pest population dynamics and evaluate the effectiveness of natural enemies (Tschanz *et al*. 2007).

Plant protection industry

The mass-rearing of insects, including YM, generates substantial quantities of by-products such as frass (insect excreta) and exuviae (molted exoskeletons). For every 1 kg of YML reared, approximately 2–3 kg of by-products are generated (Zunzunegui *et al*. 2024). These by-products are rich in essential macronutrients nitrogen (N), P, and K as well as chitin, beneficial microorganisms, and trace minerals including sulfur (S), Ca, Mg, Mn, Fe, and molybdenum (Mo). Due to this nutrient-rich composition and compatibility with soil ecosystems, YML frass is increasingly recognized as a promising organic fertilizer and biostimulant with the potential to replace synthetic mineral fertilizers and chemical pesticides. Compared to traditional fertilizers, frass nutrients are more bioavailable to plants and can enhance the abundance of plant growth-promoting rhizobacteria (PGPR), indirectly improving crop growth and yield. Moreover, frass application can boost plant tolerance to abiotic stresses such as salinity, drought, and flooding. The chitin present in frass has also been shown to trigger plant defense responses, thereby increasing resistance to pests and diseases (Poveda 2021; Barragán-Fonseca *et al*. 2022; Zunzunegui *et al*. 2024). Zunzunegui *et al*. (2024) reviewed studies published between 2019 to 2023, demonstrating the positive effect of YML frass on crop growth and resilience to environmental stress. The present work extends this review by incorporating research published through the end of 2024, as summarized in Table 7 and Table 8. As with conventional fertilizers, appropriate application methods and dosages of frass must be carefully managed based on crop species and developmental stages. Overapplication may lead to excessive soil salinity, fertilizer burn, compaction, or waterlogging, all of which can inhibit nutrient uptake and negatively impact plant growth (Zhang *et al*. 2012; Liu *et al*. 2019; Zunzunegui *et al*. 2024). The use of frass as a plant fertilizer is gaining international attention. Several commercial products have emerged, such as a pelletized frass fertilizer (5 mm granules) produced by the German company Organifer (https://organifer.com/en/), which complies with EU organic farming regulations. This product offers a nutrient composition of NPK (nitrogen, phosphorus, potassium) (3.5-3.5-2.5), along with Ca (2%), and Mg (0.7%), can be broadcast or mixed into the soil, and has low carbon emissions compared to synthetic fertilizers. Another example is a powdered frass product developed by the U.S.-based KIS Organics (https://www.kisorganics.com/), which is suitable for direct soil application, foliar spray, or use in hydroponic systems. Nevertheless, the effectiveness of frass-based fertilizers depends on multiple factors such as crop type, soil characteristics, climate conditions, and nutrient availability. Further research is necessary to optimize application protocols for scaling up its use in commercial agriculture. Such advancements could reduce dependence on synthetic fertilizers and pesticides, thereby promoting more sustainable agricultural practices. In addition to its value as fertilizer, frass also serves as a promising feedstock for biochar production. When pyrolyzed, insect frass yields high-efficiency biochar that not only enhances carbon sequestration but also exhibits strong adsorption capacities for heavy metals, making it effective for soil remediation. Compared to biochar derived from crop residues, insect-based biochar shows superior performance in adsorbing lead (Pb), Cd, chromium (Cr), Cu, and Zn (Yang *et al*. 2019; Moruzzo *et al*. 2021). These diverse applications significantly enhance the value of insect farming by-products and support innovations in circular agriculture and ecologically friendly technologies. In addition to insect frass as a fertilizer, Urrutia *et al*. (2023) demonstrated that bio-oil derived from pyrolyzed YML frass could serve as a novel biopesticide, effectively controlling

Table 7. Researches on the use of *Tenebrio molitor* frass to enhance plant growth.

Plant	Effects	References
Amaranthaceae		
Beta vulgaris L.	Increase biomass of dry plant.	Przemieniecki *et al*. (2024)
Araceae		
Philodendron pedatum (Hook.) Kunth	Increase growth and leaf greenness.	Baranimotlagh *et al*. (2024)
Araliaceae		
Panax ginseng CA Mey	Increase seed germination, plant height, leaf length, leaf width, root length, and root weight.	Kim *et al*. (2023)
Asteraceae		
Helianthus annuus L.	Increase biomass of roots, stem, flower head, whole plant and nutrition (N, P, K).[z]	Foscari *et al*. (2024)
Helminthotheca echioides (L.) Holub	Increase edible biomass (leaves number, rosette diameter, root fresh and dry weight), nutrition (P, K).[z]	Karkanis *et al*. (2025)
Sonchus oleraceus L.	Increase edible biomass (leaves number, rosette diameter, root fresh and dry weight), nutrition (P, K, Fe, Zn).[z]	Karkanis *et al*. (2025)
Brassicaceae		
Brassica oleracea L.	Increase fresh shoot weight.	van de Zande *et al*. (2024)
Brassica rapa L.	Increase leaf area.	Chia *et al*. (2024)
Strophariaceae		
Agrocybe chaxingu NL Huang	Increase edible biomass (flush fruitbody yield).	Zeng *et al*. (2017)

[z] N: nitrogen; P: phosphorus; K: potassium; Fe: iron; Zn: zinc.

Table 8. Researches on the use of *Tenebrio molitor* frass that enhances tolerance against abiotic or biotic stresses.

Plant	Effects	Abiotic/biotic stresses	References
Brassicaceae			
Arabidopsis thaliana (L.) Heynh.	Increase tolerance to biotic stress (activated systemic defenses).	*Botrytis cinerea*	Blakstad *et al*. (2023)
Fabaceae			
Phaseolus vulgaris L.	Increase tolerance to abiotic stress	Salinity, drought, flooding	Poveda *et al*. (2019)
	Increase tolerance to biotic stress (decrease disease index and incidence).	*Rhizoctonia solani*	Moarrefzadeh *et al*. (2023)

important stored-product pests such as Indian meal moth (*Plodia interpunctella* (Hübner)) and red flour beetle (*Tribolium castaneum* (Herbst)), as well as sanitary pest such as common house mosquito (*Culex pipiens* Linnaeus).

Educational materials in life sciences

To reduce the cost of larval feed, mealworm farming operations worldwide frequently use plant-based residues and by-products from the agriculture and food industries as feeding substrates. Beyond their dietary flexibility, YML have also demonstrated the ability to ingest and degrade polystyrene foam, a widely used synthetic plastic that poses significant environmental challenges. This capacity for plastic biodegradation has garnered increasing attention to YML as potential agents for plastic waste management and environmental sustainability (Siddiqui *et al*. 2024). Because of these distinctive traits, YML are increasingly used as model organisms in natural science education, environmental research, and circular agriculture studies.

Bioenergy industry

Fossil fuels are unsustainable resources, and the ongoing global energy transition necessitates the development of alternative energy solutions to reduce reliance on them. Insect oil, a form of animal fat and a key by-product of insect farming, has emerged as a promising feedstock for biofuel production. Studies have shown that insects reared on agricultural, industrial, or municipal organic by-products can accumulate substantial amounts of high-quality lipids, particularly fatty acids in the C_{16}–C_{18} range. These lipids can be converted into biodiesel using various technologies. For instance, transesterification reactions catalyzed by sodium phosphate have been used to efficiently convert YM oil into biodiesel that meets international fuel quality standards, including ASTM D6751 and EN 14214 (Siow *et al*. 2024). Consequently, insect oil is considered a novel and sustainable raw material for future biofuel production (Manzano-Agugliaro *et al*. 2012; Surendra *et al*. 2016; Baruah *et al*. 2023; Koyunoğlu 2024; Siow *et al*. 2024). Furthermore, Lee *et al*. (2022) demonstrated that YM fed with wheat bran can rapidly convert dietary carbohydrates into lipids during their larval stage. Notably, YM has a shorter growth cycle compared to many conventional oil-producing organisms, reinforcing their potential as a rapid and efficient biomass source for biofuel production. Compared to fossil fuels or traditional biofuels derived from energy crops (such as ethanol from corn or sugarcane), insect-derived oils offer superior energy efficiency and a lower carbon footprint (Koyunoğlu 2024). These characteristics make them attractive candidates for conversion into aviation-grade fuels, particularly as the aviation industry seeks to expand its use of sustainable aviation fuels (SAFs). The successful industrialization of biodiesel production from insect oils depends on the careful selection of feedstock materials, as the organic substrates used to rear insects influence the fatty acid composition of species such as the BSF and the YM. Optimizing substrate selection within circular agriculture systems is therefore essential to maximize both the quality and applicability of insect-derived oils. In addition to biodiesel, YM farming can also contribute to bioenergy production via anaerobic digestion. The residual feed and frass mixtures generated during large-scale mealworm production can be fermented to produce methane-rich biogas (Bulak *et al*. 2020). This represents a valuable energy by-product that further enhances the sustainability and resource efficiency of insect-based bioconversion systems.

Industrial ingredients

Chitin and chitosan derived from YML exhibit potential for industrial applications. Compared to crustacean-derived chitin, YML-derived chitin is softer and demonstrates superior anti-inflammatory properties, making it a uniquely advantageous raw material for the development of novel industrial products (Son *et al*. 2021). Insect-derived chitin has also been considered as an adsorbent material for the removal of dyes in the textile, leather, and paper industries. Jóźwiak *et al*. (2023) demonstrated that YML-derived chitin effectively adsorbs anionic dyes. Furthermore, Nettey-Oppong *et al*. (2025) reported that YML-derived chitosan shows promise as a sustainable sensing material for use in flexible humidity sensors, indicating potential applications in environmental monitoring, smart agriculture, and industrial process control.

Cosmetic industry

Insect-derived oils, proteins, and chitinous compounds (such as chitin and chitosan) are increasingly being explored as high-value by-products for cosmetic applications (Albushabaa & Haider 2022; Bingqian *et al*. 2023). Lipids extracted from YM contain a significant proportion of UFAs, particularly linoleic and linolenic acids. These essential fatty acids help reduce water loss through epidermis and act as lipid barriers that support skin regeneration, making them promising alternatives to plant-derived oils in cosmetic formulations (Verheyen *et al*. 2023). In addition, YML proteins are rich in amino acids, while their chitin exhibits antioxidant and antimicrobial properties (Kim *et al*. 2018; Nafary *et al*. 2023). Due to this unique biochemical composition and functional profile, YML-derived ingredients hold considerable potential as substitutes or novel components in a wide array of cosmetic products. This represents a promising economic opportunity for large-scale YM farmers, particularly those in the early stages of industrial development. By tailoring rearing and processing methods to meet specific product requirements, producers can apply suitable post-harvest treatments such as cleaning, freezing, or drying that are both cost-effective and compliant with cosmetic regulations. Target bioactive compounds can then be selectively extracted to be used either as functional ingredients (such as oils, waxes, emulsifiers) or as active ingredients (such as antioxidants, antimicrobials) across various cosmetic applications. These include skin-protective products such as hand creams, skincare creams, lip balms, and conditioner as well as cleansing formulations (such as soaps and body washes) and exfoliating treatments (such as face mask and exfoliant). However, the successful integration of YML-based ingredients into the cosmetic industry is contingent upon overcoming several challenges, including the development of safe and efficient biorefining techniques, strict quality control during production, and full compliance with cosmetic safety regulations across different countries and economic regions.

Food packaging industry

Conventional plastic packaging, primarily derived from petroleum-based sources, has greatly enhanced the convenience of modern life. However, both its production and disposal particularly via incineration are significant contributors to carbon emissions. This has spurred increasing interest in developing environmentally friendly alternatives to petroleum-based materials, thereby accelerating the advancement of the green packaging industry. Weng *et al*. (2023) reviewed the application of insect-derived proteins and chitosan as raw materials for food packaging films, revealing that chitosan-based films generally exhibit superior tensile strength compared to protein-based films. Notably, Mwita *et al*. (2024) demonstrated that chitosan films derived from YML biomass effectively extended the shelf life of bananas, highlighting their practical potential in postharvest preservation. In terms of antimicrobial functionality, protein-based films often require the incorporation of external antimicrobial agents, whereas chitosan inherently exhibits antimicrobial properties. Liu *et al*. (2024) further enhanced the physicochemical properties of chitosan films by incorporating YML proteins to improve their antioxidant and antimicrobial efficacy through the addition of propolis ethanol extract. These biodegradable and bioactive packaging materials offer promising solutions for sustainable food packaging, particularly in extending the shelf life of fresh produce and reducing reliance on petroleum-based plastics.

Biomedical materials and prospective medical research

Although chitin and its deacetylated derivative, chitosan, have been widely studied in biomedical applications, the exploration of insect-derived sources remains in its early stages. In particular, chitin and chitosan extracted from YML hold promise as sustainable and functional alternatives to conventional crustacean-derived materials (Mei *et al*. 2024), with potential applications in wound healing, tissue engineering, drug delivery, and antimicrobial therapies.

Beyond material applications, YML themselves have recently gained increasing recognition as alternative invertebrate models in medical research. Studies have demonstrated their suitability for investigating microbial pathogenesis and assessing drug toxicity, providing a cost-effective and ethically preferable substitute for conventional mammalian models such as rodents. For instance, de Souza *et al*. (2015) first validated YML as hosts for two major human fungal pathogens, *Cryptococcus neoformans* (San Felice) Vuill. and *Candida albicans* (CP Robin) Berkhout, to clarify the mechanisms of microbial pathogenesis. Subsequent studies confirmed their relevance for evaluating the virulence of *Sporothrix* species (Lozoya-Pérez *et al*. 2021), while more recent work by Brai *et al*. (2023) established a novel YML-based platform for preclinical testing of antiviral and antimicrobial agents. Collectively, these findings underscore the growing potential of YML and their derivatives as versatile resources for biomedical innovation.

CONCLUSION AND FUTURE PERSPECTIVES

With the increasing global demand for food and the mounting pressure of waste management, identifying sustainable protein sources and implementing effective resource recycling strategies have become critical priorities. Due to their high nutritional value, low environmental footprint, and capacity to biodegrade agricultural residues, YM have emerged as one of the key decomposers of plant-based waste within circular agriculture systems. They serve as a significant source of animal-derived protein for livestock feed, pet food, and treats. In Europe and the Americas, numerous companies are actively developing YML-based products for human consumption. Over the past decade, the utilization of YML as raw materials for high-value products has become a strategic focus in several national development plans. Current research indicates that YML can thrive on various plant-based substrates, such as cereal by-products and fruit and vegetable waste. However, their growth performance depends highly on the protein-to-carbohydrate ratio of the substrate, which must be carefully adjusted to optimize rearing efficiency. Concurrently, ensuring product safety requires rigorous monitoring for contaminants such as pesticide residues, heavy metals, microplastics, pathogenic microorganisms, and mycotoxins, particularly for products intended for animal feed or human consumption.

YML meal, characterized by a favorable amino acid and fatty acid composition, has been demonstrated to partially replace fishmeal and soybean meal in both livestock and aquaculture diets. Its inclusion can enhance growth performance, immunity, and feed conversion efficiency in livestock and aquatic species. However, excessive substitution levels or imbalanced nutrient profiles may negatively affect animal health, necessitating species-specific and nutritionally precise feed formulations. Furthermore, the by-products of YML farming such as frass and exuviae are rich in N, P, K, and chitin. These materials can be used in organic fertilizers, soil amendments, and stimulants, contributing to improved crop growth and disease resistance, and further expanding their value in circular agricultural systems.

When YML is reared on non-plant substrates (such as kitchen waste containing animal residues or animal by-products), safety concerns generally preclude their use in food or feed applications. However, the extracted lipids from such systems remain suitable for the bioenergy sector, including biodiesel and SAF production. In parallel, chitin derived from YM has shown promise in environmental applications, such as biosorption of heavy metals and water purification- offering added economic value beyond the food chain.

In summary, the sustainable development of the YM farming industry relies on clearly defining the types of end products and their intended applications, which in turn determines the appropriate categories of feed substrates. Such classification is essential to achieve sufficient economic scale to support industrial growth. Production systems should be designed to meet labor- and energy-saving requirements, ideally through semi-automated or fully automated farming technologies. Equally important, government authorities must establish timely and adaptive regulatory frameworks and policy instruments to guide the industry. From a technical perspective, nutritional regulation of YMs differs across breeding stages and larval growth phases, requiring tailored feed formulations to meet specific farming objectives. Risk management during rearing is also critical, including the monitoring of feedstock contamination and the control of insect-borne pathogens. Safety assessments should be conducted both on the input feed materials and on the harvested larvae to eliminate the risk of harmful residues. Furthermore, standardized farming and production protocols need to be developed so that different producers can deliver consistent, safe, and regulation-compliant products. Only by ensuring product reliability and public trust can YM farming achieve sustainable, large-scale industrialization.

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以植物基質飼養麵包蟲的多元應用：循環農業、動物飼料及其他高值化產品

謝孟祐 [1,*] 馮文斌 [1,*] 許北辰 [2] 董耀仁 [2] 李雅琳 [3] 石憲宗 [4,**]

摘要

謝孟祐、馮文斌、許北辰、董耀仁、李雅琳、石憲宗。2025。以植物基質飼養麵包蟲的多元應用：循環農業、動物飼料及其他高值化產品。台灣農業研究 74(4):415–447。

隨著全球人口持續增長，糧食供應壓力與廢棄物管理挑戰日益嚴峻，昆蟲已被視為解決此問題的重要關鍵之一。昆蟲作為有機廢棄物的生物轉化者，能將農業副產品與食品加工廢棄物等難以應用的資源轉化為有用的資源，不僅實現資源的循環再利用同時降低碳足跡，亦可有效取代傳統養殖動物飼料的蛋白質來源 (如大豆與魚粉)，從而促進農業與畜牧業的持續性發展。昆蟲可作為動物養殖飼料的原料，昆蟲含高量蛋白質與脂肪，能有效替代傳統動物飼料的魚粉等動物源蛋白質成分，為畜牧業與水產養殖之永續經營提供良好的替代方案。由於昆蟲養殖具有資源投入低、生長週期短以及生產空間需求小等優勢，使其成為一種高效且環境友善的資源利用模式，進一步推動農業朝永續發展轉型，並促進循環經濟的實現。除蟲體生物質之外，養殖過程中產生的蟲糞也是重要的副產物，其富含氮、磷、幾丁質及有益微生物，具有開發為有機肥料促進植物生長的作用，更進一步強化了麵包蟲養殖於永續循環系統中的潛力。本研究以麵包蟲 (*Tenebrio molitor*) 為例，探討其分解植物性廢棄物質的可行性與優勢，並分析飼養過程中的關鍵考量，同時評估麵包蟲幼蟲作為動物養殖飼料原料的潛力 (包含營養價值與應用案例)，以及蟲體與副產品開發成高經濟價值終端產品的應用前景。本文旨在為資源昆蟲於全球糧食供應與環境永續發展的研究，以及未來的開發方向提供完整的參考資料。相較於傳統作物與畜禽養殖，昆蟲養殖產業展現出更高的資源利用效率與更低的環境衝擊，是符合聯合國永續發展目標 (SDGs) 的綠色產業之一。

關鍵詞：麵包蟲、植物基質、循環農業、養殖動物飼料、高值化應用。

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[*] 謝孟祐與馮文斌並列第一作者。

[**] 通訊作者：htshih@tari.gov.tw
[1] 農業部農業試驗所應用動物組助理研究員。臺灣 臺中市。
[2] 農業部農業試驗所應用動物組副研究員。臺灣 臺中市。
[3] 農業部農業試驗所遺傳資源及生物技術組研究員。臺灣 臺中市。
[4] 農業部農業試驗所應用動物組研究員兼組長。臺灣 臺中市。