AB Journals

African Journal of Agriculture and Food Science
ISSN 2689-5331 • Volume 9, Issue 3, 2026 • pp. 35–56

REVIEW ARTICLE Received: 2 Sep 2026, Accepted: 22 Oct 2026, Published: 3 Nov 2026

Yellow Mealworm (Tenebrio Molitor) Production from Agricultural and Agri-Food Side-Streams: A Narrative Review of Food, Feed, Frass, Soil Health and Circular Agricultural Applications

Jane Gisemba Nyaanga*; Murerwa Patrick

Department of Crops, Horticulture and Soils, Faculty of Agriculture, Egerton University, Nakuru, Kenya.

Corresponding Author's Email: jgnyaanga@egerton.ac.ke

Abstract

Agricultural and agri-food systems generate substantial side-streams containing carbohydrates, proteins, lipids, minerals, fibre, and other valuable components that often remain underutilised or discarded. The yellow mealworm, *Tenebrio molitor*, offers an opportunity to convert selected side-streams into insect biomass and nutrient-rich frass, thereby linking resource recovery with food, feed, and crop production. This narrative review synthesises a practical circular sequence in which side-streams are characterised and screened for safety, formulated as mealworm substrates, converted into insect biomass and frass, processed into food or feed products, and returned to agriculture through frass-based soil and crop applications. The review examines how nutrient balance, moisture, fibre, digestibility, palatability, inclusion level, and contaminants influence larval performance, biomass quality, and product safety. It further evaluates mealworm-derived products and the effects of frass on soil nutrient availability, microbial activity, and crop performance. The central contribution is a connected side-stream-to-crop framework showing how mealworm biomass and frass can be managed as complementary outputs within one circular agricultural pathway. Evidence from Africa, including Kenya, remains limited, highlighting the need for locally validated substrates, safety standards, field evaluation of frass, whole-chain economic assessment, and enabling markets.

Keywords: Agricultural Side-Streams; Circular Agriculture; Frass; Insect Biomass; Soil Health; Substrate Formulation; *Tenebrio Molitor*; Yellow Mealworm

How to Cite: Nyaanga, J. G., & Murerwa, P. (2026). Yellow Mealworm (Tenebrio Molitor) Production from Agricultural and Agri-Food Side-Streams: A Narrative Review of Food, Feed, Frass, Soil Health and Circular Agricultural Applications. African Journal of Agriculture and Food Science, 9(3), 35–56. https://doi.org/10.52589/AJAFS-UZQBPE

© 2026 by the authors. Published by AB Journals. This is an open access article distributed under the terms of the Creative Commons Attribution (CC BY 4.0) license.

INTRODUCTION

Background

Sustainable food and agricultural systems must increase productivity and improve resource-use efficiency while conserving natural resources, supporting livelihoods, and strengthening resilience to climate change and market volatility (FAO, 2014). Crop production, food processing, and agro-industrial activities generate substantial quantities of side-streams containing potentially valuable constituents, including carbohydrates, proteins, lipids, minerals, fibre, cell-wall materials, and bioactive compounds. Although some of these materials are used as livestock feed, compost, bioenergy substrates, or soil amendments, many remain underutilised, poorly managed, or discarded. Their further valorisation is often constrained by seasonal availability, susceptibility to microbial deterioration, and limited industrial utilisation, resulting in the loss of valuable nutrients and other useful compounds (Schieber, 2017). The challenge is therefore not merely to minimise agricultural waste, but to develop safe, practical, and economically viable strategies that convert underutilised agricultural side-streams into valuable products and resources.

Circular agriculture promotes the recovery and continued use of biomass, nutrients, and other resources within interconnected production systems (Pena et al., 2026). Outputs from crop production, food processing, and biological conversion can become inputs for other agricultural activities, although implementation depends on technical capacity, resource availability, and economic feasibility (Madau et al., 2020; Selvan et al., 2023). Insects have attracted increasing attention within these systems because selected species can act as bioconverters, transforming suitable organic by-products into insect biomass that may be used for food and feed. However, bioconversion performance depends on insect species and substrate composition; therefore, insect-based conversion should not be regarded as a universal solution for agricultural residues (van Broekhoven et al., 2015; van Huis, 2020).

The yellow mealworm, *Tenebrio molitor* L. (Coleoptera: Tenebrionidae), is one of the most relevant insects bioconverter species because its larvae can utilise selected agricultural and agri-food side-streams to produce biomass for food and animal-feed value chains, while simultaneously generating nutrient-rich frass for potential use as a soil amendment (Debache, 2026; van Huis, 2020). Potential substrates include selected cereal, brewing, baking, potato-processing, and other agro-industrial by-products. However, their suitability cannot be determined solely by availability or classification as agricultural waste. Substrate composition and formulation influence larval development, survival, feed conversion, and biomass composition; therefore, candidate materials should be evaluated under defined rearing conditions (Oonincx et al., 2015; van Broekhoven et al., 2015; Musembi et al., 2024).

Mealworm production can therefore generate two complementary outputs: larval biomass for food and feed applications and frass for agricultural nutrient recovery. Under controlled experimental conditions, mealworm frass has supported barley growth and nutrient uptake and stimulated soil microbial activity, demonstrating its potential beyond larval biomass production (Houben et al., 2020). Nevertheless, frass responses depend on application rate, soil characteristics, environmental conditions, and crop species. Controlled experiments should therefore be complemented by comparisons with appropriate soil amendments or fertiliser treatments before frass is considered for field-scale application (Houben et al., 2020; Zunzunegui et al., 2024; Baldacchino & Lamaj, 2025).

These considerations are particularly important in Africa, especially East Africa, where cereal, potato, horticultural, and food-processing value chains generate diverse agricultural side-streams that could serve as substrates for insect production. Insect farming offers opportunities to connect suitable organic side-streams with food and feed production, nutrient recovery, and additional uses for residual materials. Realising these opportunities requires attention to production technologies, processing, markets, regulation, and economically viable value chains (Madau et al., 2020; Tanga et al., 2021). However, their extent will depend on local substrate availability, appropriate production practices, product safety, the agronomic value of frass, and the economic viability of resulting products. A comprehensive assessment should therefore reat substrate formulation, larval biomass production, food and feed applications, residual frass, and agricultural resource recovery as interconnected components of one circular production system.

Rationale, Scope and Review Question

Research on *T. molitor* spans production biology, alternative rearing substrates, nutritional composition, food and feed applications, product safety, processing, and frass utilisation. However, these areas are often considered separately, limiting an integrated understanding of the connections among substrate inputs, insect biomass, food and feed products, and agricultural nutrient recovery (van Huis, 2020; Zunzunegui et al., 2024).

This narrative review examines these connections by synthesising evidence on production biology, agricultural and agri-food side-stream utilisation, substrate formulation, larval biomass composition, food and feed applications, safety, processing and storage, and frass utilisation in soil management and crop production. It also considers economics, commercialisation, and African perspectives, with particular attention to Kenya and East Africa. Stored-product pest biology and pest management fall outside the review's scope. The guiding question is: To what extent can *T. molitor* production using agricultural and agri-food side-streams provide an integrated pathway linking insect biomass production, food and feed manufacture, frass nutrient recovery, and crop production within circular agricultural systems?

Literature Search and Information Sources

A narrative review approach was adopted because published studies differ substantially in substrate composition, feed formulation, insect stage, stocking density, environmental conditions, processing methods and outcome measures. Narrative synthesis is therefore appropriate for integrating evidence from biological, nutritional, technological, agronomic and socioeconomic studies (van Huis, 2020; Zunzunegui et al., 2024).

Literature was identified through scholarly databases, publisher platforms and reference lists using combinations of *Tenebrio molitor*, yellow mealworm, mealworm production, alternative substrates, agricultural by-products, agri-food side-streams, food waste, food, feed, safety, processing, storage, frass, soil, plant growth, crop production, circular bioeconomy, consumer acceptance, commercialisation, Africa, Kenya and East Africa.

The search emphasised literature from 2016–2026 while retaining earlier seminal studies on mealworm production, nutrition, feed conversion, food safety and processing. Peer-reviewed articles, reviews, books and chapters, and selected authoritative institutional or regulatory sources were considered.

METHODOLOGY

Eligibility Criteria

Studies were considered eligible if they addressed *Tenebrio molitor* production, agricultural and agri-food side-stream utilisation, nutritional composition, food and feed applications, safety, processing and storage, frass, soil properties, crop performance, economics, consumer acceptance, commercialisation, or African production systems. Eligible sources included original experimental and observational studies, field and controlled-environment trials, and relevant review articles. Books, book chapters, and authoritative institutional or regulatory publications were also considered where they provided relevant scientific or regulatory information.

Only English-language publications were included. Studies from all geographical regions were considered, with particular attention to Africa, East Africa, and Kenya. The review emphasised publications from 2016 to 2026 while retaining earlier seminal studies on mealworm production, nutrition, safety, and processing. Studies concerned primarily with stored-product pest biology or pest management were excluded.

Substrate Relevance and Classification

Studies investigating agricultural and agri-food side-streams, including cereal and milling residues, potato-processing waste, fruit and vegetable residues, brewery by-products, and other agro-industrial materials were prioritised. Studies using conventional feed ingredients or non-agricultural substrates were considered when they provided relevant comparative evidence on mealworm growth, nutritional composition, safety, or substrate suitability.

Mixed waste streams were included when their composition and relevance to agricultural side-stream utilisation could be established. Findings from poorly characterised or predominantly non-agricultural waste mixtures were not used to draw conclusions specifically about agricultural side-streams. This distinction prevented outcomes from being attributed to agricultural residues without sufficient supporting evidence.

Thematic Synthesis

Evidence was synthesised through thematic analysis, involving iterative reading and coding of the included publications according to their objectives, methods, and reported outcomes. Publications were assigned to one or more themes: production biology and substrate formulation, nutritional composition and insect biomass utilization, food and feed safety, processing, and storage, frass utilisation and soil health, crop performance, economics and commercialization, consumer acceptance and African production systems.

Findings were compared within and across themes to identify consistent patterns, contrasting results, knowledge gaps, and factors influencing outcomes. Studies addressing multiple stages of the production pathway were examined across themes to explore relationships among side-stream characteristics, mealworm performance, biomass quality, frass generation, and potential

Interpretation and Limitations

The synthesis was narrative rather than quantitative. Meta-analysis was not undertaken because studies differed substantially in substrate composition, experimental design, rearing conditions, insect developmental stage, and outcome measures. These differences were considered when

comparing findings, and conclusions were restricted to the conditions and outcomes supported by the available evidence.

RESULTS AND DISCUSSION

Biology and Production Management

Tenebrio molitor undergoes complete metamorphosis through egg, larval, pupal, and adult stages, with larvae constituting the principal harvested biomass (Kröncke et al 2020). Production therefore requires coordinated management of breeding adults, egg collection, larval rearing, harvesting, and post-harvest processing. Temperature, relative humidity, substrate characteristics, stocking density, and moisture availability influence development and productivity. Excessive substrate moisture can promote clumping and microbial deterioration, whereas insufficient moisture may restrict larval development. Stocking density also affects growth, survival, and feed conversion, requiring a balance between biological performance and efficient use of rearing space (Ribeiro et al., 2018).

Key production indicators include survival, development time, individual larval weight, biomass yield, feed intake, feed conversion ratio, and bioconversion efficiency. Comparisons across studies require caution because results may be reported on a fresh- or dry-matter basis, and methods for estimating feed consumption and accounting for residual substrate differ (van Broekhoven et al., 2015; Oonincx et al., 2015). Breeder management is also essential for maintaining a continuous larval supply, as adult age and sex influence reproductive performance (Resconi et al., 2026a).

At commercial scale, productivity and profitability depend on more than larval growth and feed conversion. Labour, housing, environmental control, substrate procurement, harvesting, processing, storage, and market access also influence production costs and returns. Economic assessments should therefore consider the complete production system rather than extrapolating commercial viability from laboratory performance alone (Niyonsaba et al., 2021).

Agricultural and Agri-Food Side-Streams as Formulated Substrates

Wheat bran is widely used as a rearing substrate for *T. molitor*, but agricultural and agri-food side-streams are increasingly investigated as partial or alternative feed ingredients. These include cereal and seed-cleaning residues, rice-processing by-products, brewery materials, fruit and vegetable residues, legume by-products, and potato-processing wastes (Oonincx et al., 2015; van Broekhoven et al., 2015; Rumbos et al., 2021). However, these materials should not be regarded as interchangeable. Their suitability depends on nutrient composition, moisture, fibre content, digestibility, palatability, physical characteristics, and inclusion level. Availability and low cost alone therefore do not establish their value for mealworm production.

Experimental evidence shows that alternative substrates can support larval development, although performance varies among materials and formulations. Food and organic by-product diets have affected development, survival, feed conversion, and insect composition (Oonincx et al., 2015; van Broekhoven et al., 2015). Selected seed-cleaning residues have also supported mealworm production, although their suitability differed among materials (Rumbos et al., 2021). Similarly, responses to broccoli by-product, tigernut pulp, and grape pomace varied with inclusion level while Vrontaki et al. (2024) identified differences in the suitability of

agricultural by-products. Collectively, these findings indicate that substrate suitability should be assessed against a reference diet using growth, survival, development time, and conversion efficiency, rather than larval survival alone.

Nutritional and physical differences help explain these contrasting outcomes. A residue may contain substantial protein or carbohydrate yet provide an imbalanced diet, contain poorly digestible fibre, or have physical properties that restrict feeding. Increasing its inclusion level may dilute other nutrients or alter substrate moisture and structure. Resconi et al. (2026b) highlighted the importance of physical characteristics alongside nutritional composition when evaluating rice-processing by-products. Thus, proximate composition alone may not adequately predict performance; particle size, texture, moisture retention, and accessibility also warrant consideration.

Experimental conditions further complicate comparisons. Larval developmental stage, stocking density, temperature, relative humidity, and trial duration can influence measured outcomes. Feed conversion and bioconversion estimates may also differ according to whether calculations use fresh or dry matter and how feed consumption and residual substrate are accounted for. Apparent differences among substrates may therefore reflect both biological responses and methodological variation. Clearly defined calculations, consistent reporting bases, and comparisons against reference diets are necessary for meaningful interpretation.

Substrate selection also influences the characteristics of harvested biomass. Jankauskienė et al. (2024a) and Jankauskienė et al (2024b) reported differences in the nutritional composition of larvae reared on different sustainable substrates. Such variation matters for food and feed formulation because protein, lipid, and other compositional characteristics affect suitability for particular applications. Nevertheless, differences among studies cannot automatically be attributed to diet: developmental stage, rearing conditions, processing, and analytical methods may also contribute. Substrate evaluation should therefore consider both production efficiency and the intended characteristics of the final product.

Moisture-rich potato, fruit, and vegetable residues present additional handling considerations. Their water content can increase transport requirements, complicate storage, and promote deterioration if handling is inadequate. Drying, milling, or blending may improve consistency and storage stability, but these operations introduce energy, labour, and equipment costs. Their value should therefore be assessed against demonstrated improvements in larval performance, safety, and product quality rather than assumed to be economically advantageous.

Kenyan evidence illustrates the potential of locally available materials. Musembi et al. (2024) investigated wheat bran and Irish potato waste, providing a locally relevant example of side-stream utilisation in mealworm production. However, findings from individual trials should not be generalised to all potato-processing residues because composition may vary with cultivar, processing, storage, and handling. Local validation is needed to establish suitable inclusion levels and determine whether processing or blending improves production outcomes.

Safety assessment must accompany nutritional and physical characterisation. Depending on their origin and handling, side-streams may require screening for pesticide residues, mycotoxins, heavy metals, and other relevant contaminants (Meyer et al 2021) Detection in a substrate does not, however, demonstrate transfer to or accumulation in larvae. Such conclusions require paired measurements of substrates and harvested biomass, appropriate analytical methods, and concentrations expressed on comparable reporting bases.

Overall, agricultural and agri-food side-streams are best treated as variable ingredients within formulated diets, rather than universally suitable replacements for conventional substrates. Their evaluation should combine material characterisation, safety assessment, inclusion-level trials, comparison with a reference diet, and analysis of collection, processing, and storage costs. This integrated approach avoids assuming that all available residues provide equivalent biological, nutritional, or economic benefits. Table 1 summarises selected studies examining agricultural and agri-food side-streams as substrates for *T. molitor* production.

Table 1: Selected evidence on agricultural and agri-food side-streams for *Tenebrio molitor* production

Study	Side-stream or substrate	Main outcomes evaluated	Principal evidence	Implication for production
Oonincx et al. (2015)	Food-manufacturing by-products	Survival, development, feed conversion ratio, and insect composition	Diets supported insect production, but performance varied among formulations and species.	Substrate suitability should be evaluated for the target insect species and diet formulation.
Van Broekhoven et al. (2015)	Organic by-products	Growth, survival, development, and feed conversion efficiency	Diet composition affected larval growth, survival, development, and feed conversion.	Alternative substrates should be nutritionally characterised and formulated rather than used as direct replacements.
Rumbos et al. (2021)	Seed-cleaning by-products	Survival, development, growth, and feed utilisation	Selected cereal and legume processing residues supported mealworm production, with differences among materials.	Seed-cleaning residues offer potential feed ingredients, subject to performance evaluation.
Vrontaki et al. (2024)	Agricultural by-products	Larval production performance	Production performance differed among agricultural by-products.	Candidate materials require screening before adoption.
Jankauskienė et al. (2024a)	Sustainable by-product-derived substrates	Nutritional composition and safety parameters	Substrate source influenced larval nutritional	Substrate safety and product quality should form part of diet

			composition and selected safety parameters.	formulation.
Jankauskienė et al. (2024b)	Sustainable substrates	Nutritional composition	Diet influenced the nutritional value of mealworm larvae.	Substrate selection affects both production performance and biomass quality.
Musembi et al. (2024)	Wheat bran blended with Irish potato waste	Growth, survival, bioconversion, and nutritional composition	Selected potato-waste inclusion levels improved growth and feed-conversion outcomes relative to sole wheat-bran or potato-waste diets.	Provides locally relevant evidence for incorporating potato-processing waste into mealworm diets in Kenya.
Resconi et al. (2026b)	Rice-processing by-products	Growth, survival, development, feed conversion ratio, bioconversion, and protein conversion	Performance varied with the nutritional and physical characteristics of rice side-streams.	Substrate assessment should consider nutrient composition alongside particle size, texture, moisture retention, and accessibility.
Errico et al. (2026)	Agricultural by-products	Evaluation of suitability as sustainable larval feed sources	Investigated agricultural by-products as potential feed sources for T. molitor rearing.	Supports continued evaluation of alternative substrates; specific performance outcomes should be reported according to the original study.
Meyer et al. (2021)	Insects reared on different substrates, including potentially	Chemical food-safety hazards	Identified chemical hazards relevant to insects intended for	Safety assessment should consider substrate origin and relevant

	contaminated materials	food and feed.	contaminants, alongside the safety of harvested larvae.

Biomass Composition and Food and Feed Applications

Mealworm biomass contains protein, lipids, minerals, and chitin, although its composition varies with substrate, developmental stage, rearing conditions, and post-harvest handling (Rumpold & Schlüter, 2013; Jankauskienė et al., 2024a, 2024b). Differences among studies may also reflect analytical methods, larval maturity, sample preparation, and whether results are expressed on a fresh- or dry-matter basis. Meaningful nutritional comparisons therefore require consistent sampling, analytical procedures, and reporting.

For food applications, larvae may be marketed whole or processed into dried products, powders, meals, and fractionated ingredients. Their suitability depends on nutritional composition, sensory characteristics, functional properties, and storage stability, including flavour, colour, particle size, water-holding capacity, protein functionality, and susceptibility to lipid oxidation (Rumpold & Schlüter, 2013). For feed applications, mealworms may be used as whole dried larvae, meals, or partially defatted ingredients. Their nutritional value depends on digestibility, amino-acid composition, lipid profile, chitin content, and the requirements of the target animal species, while production and processing costs influence commercial feasibility (Syahrulawal et al., 2023).

Substrate selection should therefore balance productivity with end-use suitability. A formulation that increases larval growth or biomass yield does not necessarily produce the most desirable nutritional profile for a particular application. Changes in lipid content or other compositional characteristics may affect ingredient value, processing requirements, and storage stability, while nutritional benefits may be offset by safety concerns or additional processing costs. Growth performance should consequently be assessed alongside biomass quality, safety, and intended use rather than treated as the sole criterion for substrate selection.

Food and Feed Safety, Processing and Storage

Food and feed safety must be addressed throughout the mealworm production chain, from substrate sourcing and rearing to harvesting, processing, and storage. Studies of edible insects have investigated microbial hazards and hygiene indicators, including *Salmonella*, *Staphylococcus aureus*, Enterobacteriaceae, and spore-forming bacteria such as members of the *Bacillus cereus* group (Klunder et al., 2012; Garofalo et al., 2017; Fasolato et al., 2018). However, findings from particular insect species, samples, or products should not be generalised to all mealworm products. Results require interpretation in relation to production conditions, processing treatments, sampling procedures, and microbiological methods.

The systematic reviews by Marzoli et al. (2024) and Yan et al. (2025) provide broader assessments of the microbiological status of farmed insects and insect-derived products. Together with studies of marketed insects, they support hygienic production and validated processing. Microbial outcomes nevertheless vary with substrate hygiene, rearing conditions, handling practices, initial microbial loads, and processing treatments (Vandeweyer & van der Fels-Klerx 2025). Safety management should therefore follow a risk-based approach, rather

than assuming that insect rearing either eliminates microorganisms or inevitably transfers them from substrates to harvested biomass. Chemical hazards also require assessment according to substrate origin and handling history. Agricultural side-streams may contain pesticide residues, mycotoxins, heavy metals, or other contaminants, but their presence should not be assumed in every material. Testing should reflect the source material, agricultural inputs, storage conditions, intended application, and applicable food or feed requirements. For example, cereal materials with a history of unsuitable storage may warrant mycotoxin screening, while pesticide-use records may inform residue-testing priorities. Figure 1 illustrates the production pathway, linking substrate sourcing and traceability with rearing, harvesting, processing, packaging, and product quality control. It highlights the need to manage food and feed safety throughout the circular production chain.

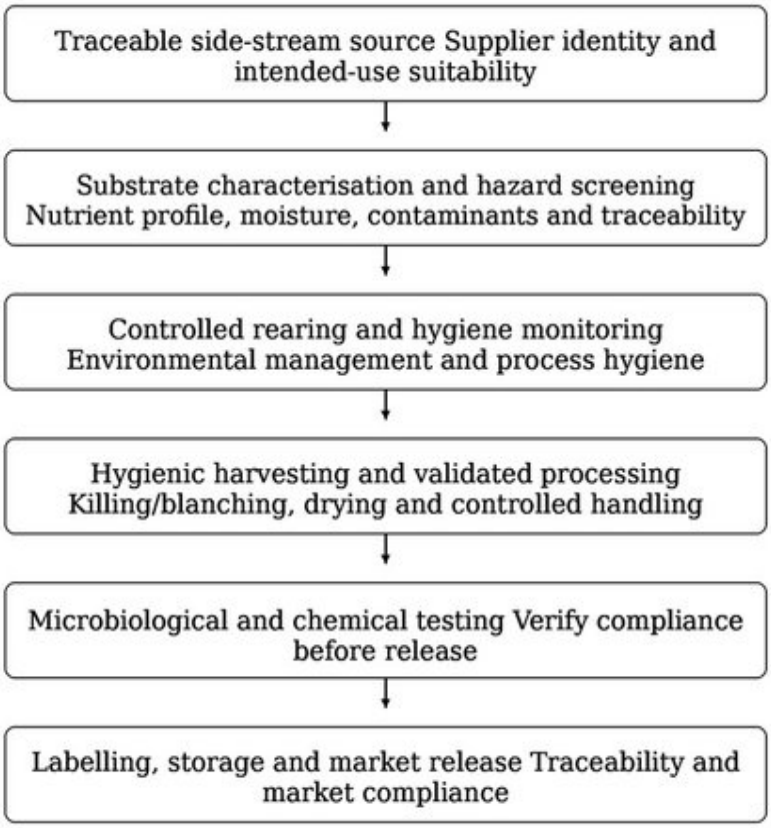


Figure 1: Safety-control pathway for converting agricultural and agri-food side-streams into compliant *T. molitor*-derived food and feed ingredients

Frass, Soil Health and Crop Production

Mealworm frass comprises insect excreta mixed with varying quantities of residual feed, exuviae, and other rearing materials. Its nutrient content and physical, chemical, and biological characteristics depend on substrate composition, mealworm development, rearing conditions, degree of substrate conversion, and post-harvest handling. Frass should therefore be evaluated as a variable soil amendment rather than assumed to be a standardised fertiliser with a uniform nutrient value (Houben et al., 2020; Zunzunegui et al., 2024).

Experimental evidence indicates that mealworm frass can supply nutrients, influence soil microbial processes, and support plant growth, biomass production, and nutrient uptake. Under controlled conditions, frass applied to barley at 10 tonnes ha^{-1} performed comparably to

nutrient-equivalent mineral NPK fertiliser in improving biomass production and nitrogen, phosphorus, and potassium uptake. Frass application also stimulated soil microbial activity (Houben et al., 2020). Similarly, mealworm frass increased ryegrass biomass relative to an untreated control, although its effectiveness as a nitrogen source depended on the application rate (Houben et al., 2021). These findings demonstrate potential fertiliser value under defined experimental conditions, but they do not establish equivalent performance across crops, soils, or field production systems.

Evidence from horticultural nursery production further illustrates the importance of crop and application rate. Low concentrations of mealworm frass improved the growth and biomass of onion, Swiss chard, and broccoli rabe seedlings, whereas higher concentrations could impair establishment (Baldacchino & Lamaj, 2025). Foscari et al. (2024) likewise reported contrasting germination responses among cress, lettuce, tomato, and sunflower, while sunflower biomass under an appropriate frass treatment was comparable with that obtained using mineral NPK fertilisation. Consequently, an application rate suitable for one crop or experimental setting may not be appropriate for another. Responses may reflect nutrient availability, amendment pH, electrical conductivity, moisture, soil properties, environmental conditions, and crop sensitivity. High nutrient concentrations do not necessarily produce greater nutrient uptake or improved growth, particularly where excessive application adversely affects growing conditions (Poveda, 2021; Zunzunegui et al., 2024).

Frass may also influence soil functioning and plant responses beyond direct nutrient supply. Watson et al. (2021) identified effects on soil microbial communities, soil processes, and metal bioavailability. Similarly, van de Zande et al. (2024) reported changes in rhizosphere bacterial communities and plant responses following amendment with insect frass and exuviae. These findings suggest potential effects on nutrient cycling and plant–soil interactions, although their mechanisms and agronomic significance require further investigation. Outcomes should also be attributed to the specific insect-derived material tested rather than generalised to mealworm frass where other insect species or residual materials were examined.

Blakstad et al. (2023) investigated the potential of frass to prime plant defence, while Karkanis et al. (2025) reported improved growth and nutritional quality in Sonchus oleraceus following combined application of frass and inorganic nitrogen fertiliser. However, these benefits may depend on the material, crop, and treatment conditions. Moreover, pot, nursery, and soil-incubation studies cannot fully capture field variability, nutrient losses, or long-term effects. Multi-season field trials are therefore needed to validate these findings and distinguish improvements in seedling growth and biomass from increases in harvested yield.

Assessment of agricultural value should combine material characterisation with crop and soil measurements. Relevant frass properties include nutrient composition, organic matter, pH, electrical conductivity, moisture, microbiological quality, and potential contaminants (Safitri et al. 2024). Crop trials should assess germination or emergence, biomass, harvested yield, nutrient uptake, soil responses, and adverse effects across multiple application rates. Comparisons should include untreated controls and appropriate mineral fertilisers or other soil amendments, with clearly reported application rates and, where appropriate, equivalent nutrient inputs.

Overall, existing evidence supports mealworm frass as a potentially useful nutrient source and soil amendment, but not as a universal replacement for mineral fertilisers. Its suitability depends on material composition, nutrient availability, crop requirements, application rate, and local growing conditions. Within circular agricultural systems, its value therefore rests on

demonstrating safe and effective nutrient recovery under practical production conditions rather than on nutrient content alone. Table 2 highlights the key evidence of mealworm frass usage in agriculture.

Table 2: Evidence of mealworm frass and insect-derived amendments in agricultural Production

Study	Experimental system or scope	Principal findings	Agronomic implications
Houben et al. (2020)	Controlled barley pot experiment	Mealworm frass applied at 10 t ha^{-1} produced biomass and N, P, and K uptake comparable to nutrient-equivalent NPK fertiliser and increased soil microbial activity.	Demonstrates nutrient potential under controlled conditions; field performance requires validation.
Houben et al. (2021)	Ryegrass pot experiment	Frass increased biomass relative to the untreated control, but its effectiveness as an N source depended on application rate.	Application rates should be optimised for the crop and growing conditions.
Poveda et al. (2019)	Controlled plant experiments	Plant responses to T. molitor frass varied with the mealworm diet; frass-associated microorganisms contributed to plant growth and responses to abiotic stress.	Frass may provide biological benefits beyond nutrient supply, although field consistency remains uncertain.
Watson et al. (2021)	Soil-incubation studies	Insect frass influenced soil microbial communities, soil processes, and metal bioavailability.	Effects depend on frass properties and soil conditions and require assessment for each application context.
Blakstad et al. (2023)	Plant experiments	Investigated the potential of insect frass to prime plant defence.	Suggests a possible role in plant protection, requiring further validation under field conditions.
Foscari et al. (2024)	Germination and	Responses varied	Crop-specific

	plant-growth tests involving cress, lettuce, tomato, and sunflower	among crops and treatments; sunflower biomass was comparable to that obtained with mineral NPK under an appropriate treatment.	responses and application rates matter; germination and biomass outcomes should not be equated with harvested yield.
van de Zande et al. (2024)	Plant–soil experiments involving insect frass and exuviae	Insect-derived amendments altered rhizosphere bacterial communities and plant responses.	Highlights potential interactions between insect-derived materials, soil microbiota, and plants.
Zunzunegui et al. (2024)	Review of yellow mealworm frass	Examined frass composition, nutrient recovery, and potential agricultural applications.	Supports the need for product characterisation and crop- and rate-specific evaluation.
Baldacchino and Lamaj (2025)	Nursery experiments with onion, Swiss chard, and broccoli rabe	Low frass concentrations improved seedling growth, whereas higher concentrations could impair establishment.	Application rates should be optimised to avoid adverse effects during seedling establishment.
Karkanis et al. (2025)	Sonchus oleraceus grown with frass and inorganic nitrogen fertiliser	Combined application improved plant growth and nutritional characteristics.	Frass may complement mineral fertiliser, but treatment comparisons should distinguish the effects of frass from those of added nitrogen.

Circularity, Economics and Commercialisation

Circularity should be evaluated across the entire production chain rather than by considering only the conversion of side-streams into insect biomass. Collection, transport, drying, milling, storage, environmental control, rearing, harvesting, processing, packaging, and distribution all require resources and generate costs (Niyonsaba et al., 2021). A system may therefore improve waste valorisation at the insect-rearing stage while remaining economically or environmentally constrained elsewhere in the chain.

The economic value of T. molitor production depends on whether sufficient value is retained after these inputs are considered. Transporting wet, low-value side-streams over long distances, or drying them using expensive energy, can substantially reduce profitability. Local production close to cereal mills, potato processors, seed-cleaning facilities, breweries, or horticultural processors may reduce these constraints where safe, consistent side-streams are available. Proximity can lower transport requirements and support more reliable substrate supply, but it does not re

Figure 2 illustrates the circular pathway linking agricultural and agri-food side-streams with *T. molitor* production, biomass valorisation, frass recovery, and crop production. This pathway integrates side-stream characterisation and substrate formulation with insect-based food and feed production and nutrient recovery through frass, which supports crop production and generates new side-streams for subsequent rearing cycles.

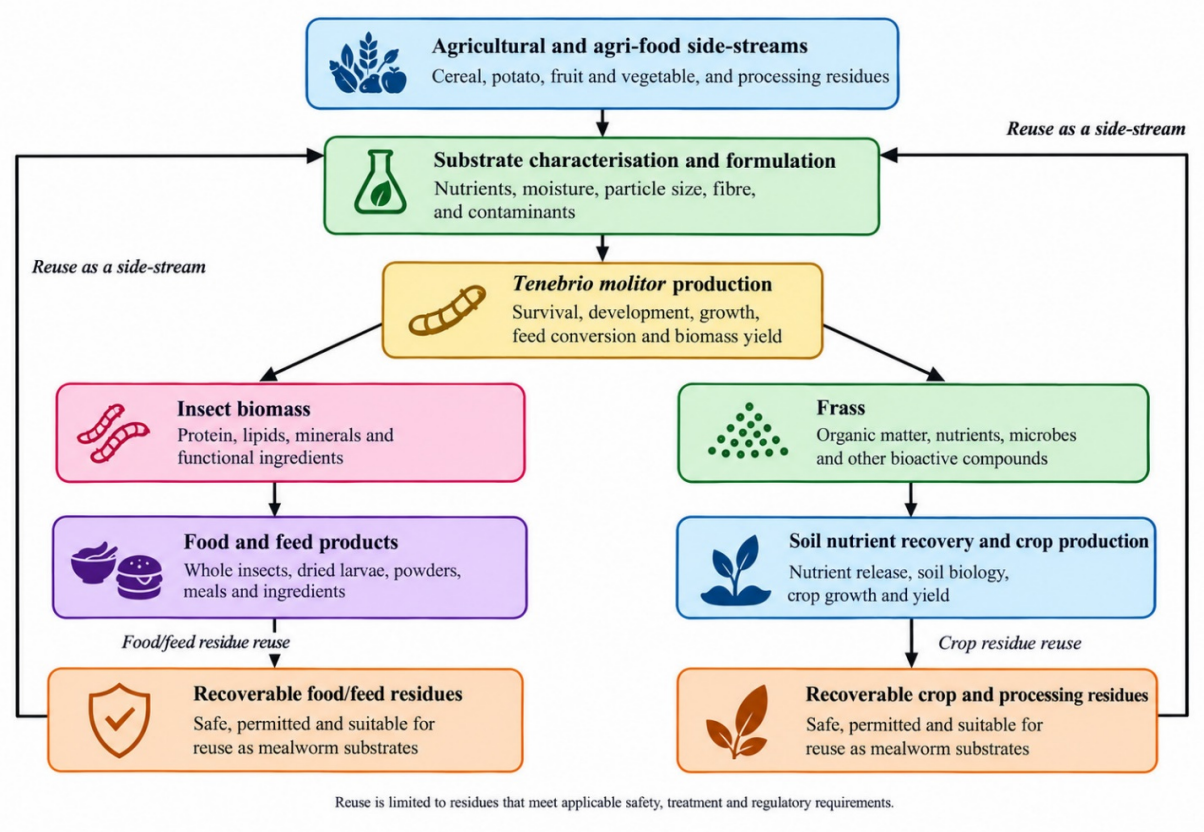


Figure 2: Circular production pathway for *Tenebrio molitor* using agricultural and agri-food side-streams

African Opportunities and Constraints

Africa has substantial potential for insect-based circular agriculture because agricultural and food-processing systems generate diverse organic side-streams, while farmers face constraints related to feed costs, soil fertility, and access to external inputs (Kelemu et al., 2015; Tanga et al., 2021). In this context, T. molitor production could contribute to feed supply, waste valorisation, and nutrient recovery, provided that production systems are adapted to local materials, infrastructure, and market conditions.

East Africa has an emerging insect-based food and feed sector, although production, market, and regulatory challenges remain (Tanga & Kababu, 2023). Potential mealworm substrates

include cereal bran, potato-processing residues, horticultural materials, fruit and vegetable side-streams, seed-cleaning by-products, and selected brewery residues. Their availability and composition vary seasonally and among processors, making substrate sourcing and quality control important elements of system design.

Kenya is particularly relevant because of its cereal, potato, and horticultural value chains. The study by Musembi et al. (2024) provides direct evidence that Irish potato-processing waste can be incorporated into mealworm diets, illustrating the potential for linking food-processing enterprises with insect production. Such linkages may reduce disposal pressures for processors while providing a locally available substrate for insect producers. However, practical implementation requires reliable agreements on substrate supply, collection, transport, storage, and quality assurance.

African production systems face constraints related to seasonal substrate availability, variable composition, high moisture, spoilage, drying, storage, transport, access to finance, and technical skills (Niassy et al 2025). Wet or perishable residues may be difficult to store and transport, while drying can add cost and energy demand. Local production systems therefore require dependable substrate-sourcing arrangements, appropriate handling and storage procedures, and quality-control protocols to reduce variation in larval performance and product safety.

Kenyan studies indicate that farmers' knowledge, perceived quality, price, and confidence influence attitudes towards commercial insect-based feed products (Chia et al., 2020; Okello et al., 2021). These market factors should be considered alongside biological performance and production costs. A technically feasible substrate may not support commercial development if it produces inconsistent products, creates safety concerns, or cannot be supplied reliably at an acceptable price.

Scaling should therefore involve coordinated development of substrate supply chains, farmer and producer training, processing facilities, quality assurance, market systems, financing, and appropriate regulatory frameworks (Kelemu et al., 2015; Tanga & Kababu, 2023). Investment in one component alone is unlikely to be sufficient: reliable substrate supply must be matched with production capacity, processing and storage infrastructure, product standards, and access to buyers.

Future studies should therefore evaluate the linked pathway using consistent measurements of substrate composition, larval performance, biomass quality, relevant hazards, frass characteristics, and crop responses. This integrated approach is particularly important for locally sourced side-streams in Kenya and East Africa, where material composition, processing infrastructure, and production conditions may differ from those represented in the existing literature.

RESEARCH GAPS AND IMPLICATIONS FOR RESEARCH AND PRACTICE

Substrate and Production Standardisation

Future studies should consistently report substrate dry matter, moisture, protein, lipid, fibre, ash, antinutritional factors, particle characteristics, and contaminants. Production performance should also be reported using standardised indicators, including larval stage, stocking density, temperature, relative humidity, survival, development time, biomass yield, feed intake, feed

conversion, and bioconversion efficiency (Ribeiro et al., 2018; Oonincx et al., 2015). Consistent reporting would improve comparability across studies and support more reliable identification of substrates and rearing conditions suitable for local production systems.

Greater emphasis should be placed on multi-substrate formulations rather than single-material substitution. Single side-streams may be nutritionally incomplete, highly variable, or impractical to supply continuously, whereas blended substrates can balance nutrients, moisture, and physical properties. Future work should therefore assess biological performance and economic feasibility simultaneously, rather than treating substrate suitability as a purely biological question (Resconi et al., 2026b).

Safety and Processing

Full-chain safety research is required for locally available African side-streams. Priority should be given to microbial pathogens, mycotoxins, pesticide residues, heavy metals, and allergenicity, with sampling and testing aligned to substrate origin, storage conditions, and intended product use (Marzoli et al., 2024; Yan et al., 2025). Safety assessment should extend from incoming substrates through rearing, harvesting, processing, storage, and final products.

Low-cost and energy-efficient processing systems suitable for decentralised production should also be evaluated. Research should assess their effects on microbial safety, nutritional quality, shelf life, processing losses, and operating costs (Ribeiro et al., 2024). This is particularly important where electricity access, drying capacity, cold storage, and quality-assurance infrastructure are limited.

Frass and Field Validation

Frass characterisation should be standardised so that studies can distinguish effects associated with nutrient supply from those associated with organic matter, microbial communities, pH, electrical conductivity, or contaminants. Multi-season field experiments should compare frass with mineral fertilisers, compost, manure, and integrated nutrient-management approaches under locally relevant soil and cropping conditions (Houben et al., 2020; Watson et al., 2021; Zunzunegui et al., 2024).

Research should measure crop yield, nutrient-use efficiency, soil organic matter, microbial activity, nutrient availability, salinity, nutrient losses, and profitability. Greater attention should also be given to whether frass derived from different mealworm substrates produces different agronomic responses. This is essential because substrate composition and rearing conditions may influence frass quality, while crop responses may vary with soil type, climate, application rate, and crop species.

Economics, Markets and Policy

Economic studies should assess the complete chain from side-stream acquisition to biomass and frass marketing. Household, cooperative, processor-linked, and commercial production models should be compared using consistent measures of substrate and logistics costs, production performance, processing losses, product prices, and market access (Niyonsaba et al., 2021; Niyonsaba et al., 2024). Such studies should identify the production scales and business models most likely to be viable in East African contexts.

Food, feed, protein ingredients, whole insects, and frass should be evaluated separately because their processing, quality, regulatory, and market requirements differ. Consumer and farmer

acceptance research should be linked with product quality, price, safety information, and supply reliability rather than treated as independent from technical development (Chia et al., 2020; Okello et al., 2021). Policy and regulatory research should likewise address substrate use, product classification, traceability, quality assurance, and market access.

Review Limitations

This review is narrative rather than systematic and therefore does not provide pooled quantitative treatment effects. Considerable heterogeneity exists among studies in substrates, experimental designs, environmental conditions, insect stages, and outcome measures. Evidence is also geographically uneven, with substantially more research conducted outside Africa than within African production systems.

Commercial-scale production, full-chain economics, local processing, market development, and multi-season field validation of mealworm frass remain comparatively under-researched. Consequently, the conclusions presented here should be interpreted as an evidence-informed synthesis rather than universal recommendations. Their application should be adapted to local substrate availability, production capacity, regulatory requirements, and market conditions.

CONCLUSIONS

Tenebrio molitor has potential to contribute to circular agriculture by connecting agricultural and agri-food side-streams with biomass production for food and feed, and with frass for agricultural nutrient recovery. However, this potential depends on substrate suitability, formulation, production management, safety, processing, product quality, markets, and appropriate use of frass (van Huis, 2020; Zunzunegui et al., 2024). The value of the system therefore cannot be assessed from larval growth alone; it must be considered across the entire production and valorisation pathway.

Side-streams should be treated as variable feed resources requiring characterisation rather than as generic wastes. Appropriate materials can support mealworm production, but nutrient balance, moisture, fibre, physical properties, inclusion level, and safety remain critical (Oonincx et al., 2015; Resconi et al., 2026b). Multi-substrate formulations are likely to be more practical than reliance on a single residue, particularly where side-stream availability and composition vary seasonally. Insect biomass can be directed towards food or feed markets, while frass can provide a complementary nutrient and organic-matter resource.

Frass research demonstrates both potential and caution. Beneficial effects on nutrient availability, soil biological processes, and crop performance have been reported, but responses vary with application rate, soil properties, and crop species (Houben et al., 2020; Foscari et al., 2024; Zunzunegui et al., 2024). Frass should therefore be evaluated as part of integrated nutrient management rather than assumed to universally replace mineral fertiliser. Its agronomic value depends on consistent characterisation, safe handling, appropriate application rates, and validation under local field conditions.

For Kenya and East Africa, development should focus on locally adapted and traceable systems that link reliable side-stream sources with safe insect production, suitable processing, diversified markets, and validated agricultural use of frass. This requires coordinated attention to substrate supply, quality assurance, production capacity, processing infrastructure, market

development, financing, and regulatory compliance. Farmer and consumer acceptance should also be considered alongside technical and economic performance.

Future research should move beyond isolated assessments of larval growth or substrate substitution towards integrated evaluation of the complete circular pathway. Such research should begin with the characterisation and formulation of agricultural and agri-food side-streams as rearing substrates for *T. molitor* production. The resulting insect biomass can then be valorised as human food or animal feed, while frass can be recovered as a nutrient-rich soil amendment to support crop production, thereby generating new agricultural and agri-food side-streams that re-enter the production cycle.

This integrated approach can provide a stronger scientific basis for evaluating the contribution of yellow mealworm production to resource efficiency, enterprise development, and circular agricultural systems. In particular, it can help identify which locally available side-streams, production configurations, and product pathways are both biologically feasible and economically viable under Kenyan and East African conditions.

Acknowledgments

The authors acknowledge all sources of information as cited in the manuscript/paper.

Funding

The authors declare that no specific external funding was received for preparation of this review.

Conflict of Interest

The authors declare no conflict of interest.

AI use declaration

AI tools including ChatGPT and Perplexity supported language and figure formatting. The authors independently checked citations against source documents and reviewed the manuscript for consistency; responsibility for the final content remains with the author.s

Author Contribution

J. G. Nyaanga conceived the review, developed the framework, analysed the literature, interpreted findings, prepared and submitted the manuscript.

P. Murerwa did literature review and analysis

Data Availability

No new datasets were generated or analysed for this narrative review.

REFERENCES

Baldacchino, F., & Lamaj, F. (2025). Application of mealworm frass in organic seedling production of Allium cepa L., Beta vulgaris L., and Brassica rapa L. Seeds, 4(1), Article 4. https://doi.org/10.3390/seeds4010004

Blakstad, J. I., Strimbeck, R., Poveda, J., Bones, A. M., & Kissen, R. (2023). Frass from yellow mealworm (Tenebrio molitor) as plant fertilizer and defense priming agent. Biocatalysis and Agricultural Biotechnology, 53, Article 102862. https://doi.org/10.1016/j.bcab.2023.102862

Chia, S. Y., Macharia, J., Diiro, G. M., Kassie, M., Ekesi, S., van Loon, J. J. A., Dicke, M., & Tanga, C. M. (2020). Smallholder farmers' knowledge and willingness to pay for commercial insect-based feeds in Kenya. PLOS ONE, 15(3), Article e0230552. https://doi.org/10.1371/journal.pone.0230552

Debache, K. (2026). Yellow mealworm (Tenebrio molitor) 2020–2025 evidence for circular bioeconomy and key sustainability constraints. Peer Community Journal, 6, Article e42. https://doi.org/10.24072/pcjournal.722

FAO. (2014). Building a common vision for sustainable food and agriculture: Principles and approaches. Food and Agriculture Organization of the United Nations. https://openknowledge.fao.org/handle/20.500.14283/i3940e

Fasolato, L., Cardazzo, B., Carraro, L., Fontana, F., Novelli, E., & Balzan, S. (2018). Edible processed insects from e-commerce: Food safety with a focus on the *Bacillus cereus* group. *Food Microbiology, 76*, 296–303. https://doi.org/10.1016/j.fm.2018.06.008

Foscari, A., Dalla Costa, L., Tulli, F., Uboni, C., & Fellet, G. (2024). Frass from Tenebrio molitor as alternative to NPK-mineral fertilization: Results from a germination test and pot experiment on sunflower. Italian Journal of Agronomy, 19, Article 100010. https://doi.org/10.1016/j.ijagro.2024.100010

Garofalo, C., Osimani, A., Milanović, V., Taccari, M., Cardinali, F., Aquilanti, L., Riolo, P., Ruschioni, S., Isidoro, N., & Clementi, F. (2017). The microbiota of marketed processed edible insects as revealed by high-throughput sequencing. Food Microbiology, 62, 15–22. https://doi.org/10.1016/j.fm.2016.09.012

Hénault-Ethier, L., Reid, B., Hotte, N., Paris, N., Quinche, M., Lachance, C., Fortin, A., Normandin, É., Laderriere, V., & Vandenberg, G. (2023). Growth trials on vegetables, herbs, and flowers using mealworm frass, chicken manure, and municipal compost. ACS Agricultural Science & Technology, 3(3), 249–259. https://doi.org/10.1021/acsagscitech.2c00217

Houben, D., Daoulas, G., Faucon, M.-P., & Dulaurent, A.-M. (2020). Potential use of mealworm frass as a fertilizer: Impact on crop growth and soil properties. Scientific Reports, 10, Article 4659. https://doi.org/10.1038/s41598-020-61765-x

Houben, D., Daoulas, G., & Dulaurent, A.-M. (2021). Assessment of the short-term fertilizer potential of mealworm frass using a pot experiment. Frontiers in Sustainable Food Systems, 5, Article 742540. https://doi.org/10.3389/fsufs.2021.742540

Jankauskienė, A., Aleknavičius, D., Andrulevičiūtė, V., Mockus, E., Bartkienė, E., Juknienė, I., Kiseliovienė, S., Zavistanavičiūtė, P., Zaborskienė, G., & Kabašinskienė, A. (2024a). Nutritional composition and safety parameters of mealworms (Tenebrio molitor) reared on substrates derived from by-products. Applied Sciences, 14(7), Article 2744. https://doi.org/10.3390/app14072744

Jankauskienė, A., Aleknavičius, D., Kiseliovienė, S., Antanaitis, Š., Falkauskas, R., Šumskienė, M., Juknienė, I., & Kabašinskienė, A. (2024b). The influence of different sustainable substrates on the nutritional value of Tenebrio molitor larvae. Foods, 13(3), Article 365. https://doi.org/10.3390/foods13030365

Karkanis, A., Ntatsi, G., Vasilakakou, E., Karavidas, I., Ntanasi, T., Rumbos, C. I., & Athanassiou, C. G. (2025). Combining Tenebrio molitor frass with inorganic nitrogen fertilizer to improve soil properties, growth parameters, and nutrient content of Sonchus oleraceus crop. Bioresource Technology, 418, Article 131901. https://doi.org/10.1016/j.biortech.2024.131901

Kelemu, S., Niassy, S., Torto, B., Fiaboe, K., Affognon, H., Tonnang, H., Khamis, F., & Roos, N. (2015). African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. Journal of Insects as Food and Feed, 1(2), 103–119. https://doi.org/10.3920/JIFF2014.0016

Klunder, H. C., Wolkers-Rooijackers, J., Korpela, J. M., & Nout, M. J. R. (2012). Microbiological aspects of processing and storage of edible insects. Food Control, 26(2), 628–631. https://doi.org/10.1016/j.foodcont.2012.02.013

Kröncke, N., Baur, A., Böschen, V., Demtröder, S., Benning, R., & Delgado, A. (2020). Automation of insect mass rearing and processing technologies of mealworms (Tenebrio molitor). In A. M. Aladjadjiyan (Ed.), African edible insects as alternative source of food, oil, protein and bioactive components (pp. 123–139). Springer. https://doi.org/10.1007/978-3-030-32952-5_8

Madau, F. A., Arru, B., Furesi, R., & Pulina, P. (2020). Insect farming for feed and food production from a circular business model perspective. Sustainability, 12(13), Article 5418. https://doi.org/10.3390/su12135418

Marzoli, F., Bertola, M., Pinarelli Fazion, J., Cento, G., Antonelli, P., Dolzan, B., Barco, L., & Belluco, S. (2024). A systematic review on the occurrence of Salmonella in farmed Tenebrio molitor and Acheta domesticus or their derived products. International Journal of Food Microbiology, 410, Article 110464. https://doi.org/10.1016/j.ijfoodmicro.2023.110464

Meyer, A., Meijer, N., Hoek-van den Hil, E. F., & van der Fels-Klerx, H. J. (2021). Chemical food safety hazards of insects reared for food and feed. *Journal of Insects as Food and Feed*, 7(5), 823–831. https://doi.org/10.3920/JIFF2020.0085

Musembi, J. P., Owino, E. A., Oyieke, F. A., Tanga, C. M., Beesigamukama, D., Subramanian, S., Cheseto, X., & Egonyu, J. P. (2024). Efficient agri-food waste valorization using mealworm (Coleoptera: Tenebrionidae) into nutrient-rich biomass for food and feed. Journal of Economic Entomology, 117(4), 1242–1253. https://doi.org/10.1093/jee/toae035

Niyonsaba-van den Hoorn, H. H., Höhler, J., Kooistra, J., van der Fels, H. J., & Meuwissen, M. P. M. (2021). Profitability of insect farms. Journal of Insects as Food and Feed, 7(5), 923–934. https://doi.org/10.3920/JIFF2020.0087

Niyonsaba-van den Hoorn, H. H., Höhler, J., Kooistra, J., van der Fels, H. J., & Meuwissen, M. P. M. (2024). Profitability of insect production for T. molitor farms in the Netherlands. Journal of Insects as Food and Feed, 10(6), 895–907. DOI: 10.1163/23524588-20230154

Nogalska, A., Przemieniecki, S. W., Krzebietke, S. J., Załuski, D., Kosewska, A., Skwierawska, M., & Sienkiewicz, S. (2023). The effect of mealworm frass on the chemical and microbiological properties of horticultural peat in an incubation experiment. International Journal of Environmental Research and Public Health, 20(1), Article 21. https://doi.org/10.3390/ijerph20010021

Okello, A. O., Nzuma, J. M., Otieno, D. J., Kidoido, M., & Tanga, C. M. (2021). Farmers' perceptions of commercial insect-based feed for sustainable livestock production in Kenya. Sustainability, 13(10), Article 5359. https://doi.org/10.3390/su13105359

Oonincx, D. G. A. B., van Broekhoven, S., van Huis, A., & van Loon, J. J. A. (2015). Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLOS ONE, 10(12), Article e0144601. https://doi.org/10.1371/journal.pone.0144601

Pena, M. A. G., dos Anjos, S. S. N., & Leitão, F. O. (2026). Circular economy in agrifood RD&I: A global bibliometric review. Circular Economy and Sustainability, 6, Article 352. https://doi.org/10.1007/s43615-026-01074-z

Poveda, J. (2021). Insect frass in the development of sustainable agriculture: A review. Agronomy for Sustainable Development, 41, Article 6. https://doi.org/10.1007/s13593-020-00656-x

Poveda, J., Jiménez-Gómez, A., Saati-Santamaría, Z., Usategui-Martín, R., Rivas, R., & García-Fraile, P. (2019). Mealworm frass as a potential biofertilizer and abiotic stress tolerance-inductor in plants. Applied Soil Ecology, 142, 110–122. https://doi.org/10.1016/j.apsoil.2019.04.016

Resconi, A., Adamaki-Sotiraki, C., Rigopoulou, M., Gasco, L., & Athanassiou, C. G. (2026a). Is age just a number? Sex-specific age effects on the reproduction of yellow mealworm. Animal, 20(8), Article 101884. https://doi.org/10.1016/j.animal.2026.101884

Resconi, A., Loiotine, Z., Bellezza Oddon, S., Passaro, R. L., Mendez Rondo, K. Y., Aiuto, B., Bacenetti, J., Gasco, L., & Biasato, I. (2026b). Rice by-product-based diets as rearing substrates for yellow mealworm: Physical characteristics and nutritional content interplay on larval growth. Animal, 20, Article 101835. https://doi.org/10.1016/j.animal.2026.101835

Ribeiro, J. C., Marques, J. P., Fernandes, T. R., Estevez Pintado, M., Carvalho, S. M. P., & Cunha, L. M. (2024). Effect of blanching, storage and drying conditions on the macro-composition, color and safety of mealworm Tenebrio molitor larvae. LWT, 191, Article 115646. https://doi.org/10.1016/j.lwt.2023.115646

Ribeiro, N., Abelho, M., & Costa, R. (2018). A review of the scientific literature for optimal conditions for mass rearing Tenebrio molitor (Coleoptera: Tenebrionidae). Journal of Entomological Science, 53, 434–454. https://doi.org/10.18474/JES17-67.1

Rumbos, C. I., Bliamplias, D., Gourgouta, M., Michail, V., & Athanassiou, C. G. (2021). Rearing Tenebrio molitor and Alphitobius diaperinus larvae on seed cleaning process byproducts. Insects, 12(4), Article 293. https://doi.org/10.3390/insects12040293

Rumpold, B. A., & Schlüter, O. K. (2013). Nutritional composition and safety aspects of edible insects. Molecular Nutrition & Food Research, 57(5), 802–823. https://doi.org/10.1002/mnfr.201200735

Safitri, R.A., Vandeweyer, D., Deruytter, D., Meijer, N., Coudron, C.L., Banach, J.L., & van der Fels-Klerx, H.J. (2024). Exploring potential uses of insect frass for agricultural production considering its nutrients, and chemical and microbiological safety. *Journal of Insects as Food and Feed*, *11*(17), 167-190. https://doi.org/10.1163/23524588-00001224

Schieber, A. (2017). Side streams of plant food processing as a source of valuable compounds: Selected examples. Annual Review of Food Science and Technology, 8, 97–112. DOI: 10.1146/annurev-food-030216-030135

Selvan, T., Panmei, L., Murasing, K. K., Guleria, V., Ramesh, K. R., Bhardwaj, D. R., Thakur, C. L., Kumar, D., Sharma, P., Digvijaysinh Umedsinh, R., Kayalvizhi, D., & Deshmukh, H. K. (2023). Circular economy in agriculture: Unleashing the potential of integrated organic farming for food security and sustainable development. Frontiers in Sustainable Food Systems, 7, Article 1170380. https://doi.org/10.3389/fsufs.2023.1170380

Syahrulawal, L., Torske, M. O., Sapkota, R., Næss, G., & Khanal, P. (2023). Improving the nutritional values of yellow mealworm (Tenebrio molitor) (Coleoptera: Tenebrionidae) larvae as an animal feed ingredient: A review. Journal of Animal Science and Biotechnology, 14, Article 146. https://doi.org/10.1186/s40104-023-00945-x

Tanga, C. M., Egonyu, J. P., Beesigamukama, D., Niassy, S., Kimathi, E., Magara, H. J. O., Omuse, E. R., Subramanian, S., & Ekesi, S. (2021). Edible insect farming as an emerging and profitable enterprise in East Africa. Current Opinion in Insect Science, 48, 64–71. https://doi.org/10.1016/j.cois.2021.09.007

Tanga, C. M. & Kababu, M. O. (2023). New insights into the emerging edible insect industry in Africa. Animal Frontiers, 13(4), 26–40. https://doi.org/10.1093/af/vfad039

van Broekhoven, S., Oonincx, D. G. A. B., van Huis, A., & van Loon, J. J. A. (2015). Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. Journal of Insect Physiology, 73, 1–10. https://doi.org/10.1016/j.jinsphys.2014.12.005

van de Zande, E. M., Wantulla, M., van Loon, J. J. A., & Dicke, M. (2024). Soil amendment with insect frass and exuviae affects rhizosphere bacterial community, shoot growth and carbon/nitrogen ratio of a brassicaceous plant. Plant and Soil, 495, 631–648. https://doi.org/10.1007/s11104-023-06351-6

van Huis, A. (2013). Potential of insects as food and feed in assuring food security. Annual Review of Entomology, 58, 563–583. https://doi.org/10.1146/annurev-ento-120811-153704

van Huis, A. (2020). Insects as food and feed, a new emerging agricultural sector: A review. Journal of Insects as Food and Feed, 6(1), 27–44. https://doi.org/10.3920/JIFF2019.0017

Vrontaki, M., Adamaki-Sotiraki, C., Rumbos, C. I., Anastasiadis A & Athanassiou C. G. (2024). Valorization of local agricultural by-products as nutritional substrates for *Tenebrio molitor* larvae: A sustainable approach to alternative protein production. *Environmental Science and Pollution Research, 31*, 35760–35768. https://doi.org/10.1007/s11356-024-33564-8

Watson, C., Schlösser, A., Vögerl, J., & Wichern, F. (2021). Excellent excrement? Frass impacts on a soil's microbial community, processes and metal bioavailability. Applied Soil Ecology, 168, Article 104110. https://doi.org/10.1016/j.apsoil.2021.104110

Yakti, W., Schulz, S., Förster, N., Deruytter, D., Müller, M., Mewis, I., & Ulrichs, C. (2025). Utilising common bean and strawberry vegetative wastes in yellow mealworm (Tenebrio molitor) substrates: Effects of pre-treatment on growth and composition. Scientific Reports, 15, Article 7772. https://doi.org/10.1038/s41598-025-91732-3

Yan, X., Brulé, L., Munir, M. T., Federighi, M., Cappelier, J.-M., Jury, V., Misery, B., & Boué, G. (2025). Systematic review of the microbiological status of farmed and processed Tenebrio molitor: Insights on foodborne pathogens in food and feed applications. Food Control, 176, Article 111340. https://doi.org/10.1016/j.foodcont.2025.111340

Zunzunegui, I., Martín-García, J., Santamaría, Ó., & Poveda, J. (2024). Analysis of yellow mealworm (Tenebrio molitor) frass as a resource for a sustainable agriculture in the current context of insect farming industry growth. Journal of Cleaner Production, 460, Article 142608. https://doi.org/10.1016/j.jclepro.2024.142608