Review

Not peer-reviewed version

Yellow Mealworm (*Tenebrio molitor*) 2020–2025 Evidence for Circular Bioeconomy and Key Sustainability Constraints

Karim Debache [*]

Posted Date: 16 April 2026

doi: 10.20944/preprints202509.0944.v5

Keywords: yellow mealworm; *Tenebrio molitor*; edible insects; circular bioeconomy; EU novel food; safety; allergenicity; life-cycle assessment; frass; chitosan; feed; sustainability constraints doi:10.20944/preprints202509.0944.v5

Review

Yellow Mealworm (*Tenebrio molitor*) 2020–2025 Evidence for Circular Bioeconomy and Key Sustainability Constraints

Karim Debache

Independent Researcher, Bern, Switzerland; karim.debache@debache.ch

Abstract

The yellow mealworm, *Tenebrio molitor* (*T. molitor*), is increasingly considered a promising protein and lipid source for circular bioeconomy strategies in food and feed. Interest is driven by the need to diversify protein supplies and reduce environmental footprints, but feasibility depends on safety, regulation, and scalable operating conditions. Alongside industrial systems, low-input models adapted to arid conditions have been proposed, yet evidence remains heterogeneous and context-dependent. This review covers developments between 2020 and 2025, a period that coincides with accelerated EU novel food assessments and a rapid expansion of applied research on processing, safety, and valorization, with a focus on scientific progress and regulatory approvals such as those issued by EFSA in Europe. Several new applications have emerged, including enzymatic hydrolysates, lipid recovery, and the extraction of chitosan from exuviae. Uses now span animal nutrition, biodegradable materials, and bioactive food ingredients. Life-cycle assessments often report lower greenhouse gas emissions and land use than conventional livestock, but outcomes are sensitive to energy inputs, feed substrates, and system boundaries. Key constraints include variable frass composition, allergenicity and cross-reactivity risks, regulatory and compliance constraints, and mixed consumer acceptance. For research, priority needs include longer-term safety datasets and field-relevant validation of bioactive claims beyond in vitro assays. For policy and industry, priorities include harmonised criteria for substrate safety and traceability, and transparent supply-chain controls that enable reproducible quality at scale.

Keywords: yellow mealworm; *Tenebrio molitor*; edible insects; circular bioeconomy; EU novel food; safety; allergenicity; life-cycle assessment; frass; chitosan; feed; sustainability constraints

---

1. Introduction

The accelerating global population and growing environmental pressures are reinforcing the search for new food sources, especially sustainable proteins [1]. According to recent life-cycle assessments, mealworm farming has a comparatively low footprint. In Austria, Dreyer and collaborators estimated that producing 1 kg of edible protein results in 20.4 kg CO_2-eq, 213.7 MJ of non-renewable energy use, and 22.4 m^2 of land occupation. Compared with organic broiler, impacts were 18-72 % lower across most categories, except for freshwater eutrophication, which was slightly higher [2]. In this context, the yellow mealworm (*Tenebrio molitor*, *T. molitor*) is a relevant model to discuss sustainable protein supply and co-product valorisation within circular bioeconomy strategies. The arid-zone model is here defined as a decentralized, low-input farming system. It operates under scarce water conditions, strong day/night temperature fluctuations, and relies on irregular local waste streams with minimal capital or energy infrastructure. Among edible insects, this species is notable for its balanced nutritional profile, low environmental footprint, and potential to integrate into circular bioeconomy models [3]. Recent research has also highlighted the multi-sectoral value of its biomass. The exuviae are a promising source of high-quality chitosan with applications in food packaging and biomedical materials [4], while its frass and oils are increasingly incorporated into agricultural and cosmetic products [5,6]. Over the past five years, investigations have shifted from basic feasibility studies [7] to advanced applications. New findings include bioactive protein hydrolysates with antioxidant properties [8], functional peptides, and decentralized low-tech farming systems adapted to rural contexts [9]. At a more mechanistic level, tachykinin-related peptides have been reported to modulate immune-gene expression in the mealworm beetle, illustrating the expansion of functional biology around *T. molitor* beyond nutritional profiling [10]. From a regulatory perspective, *T. molitor* has progressively gained Novel Food recognition in Europe. Pioneering policies outside the EU have also supported its early commercialization [11]. This evolving legal framework underscores the growing institutional interest in insect-based proteins. Across alternative protein categories, unclear regulatory guidance and uneven safety evidence can still slow uptake, including for insect-based products [12]. Technological innovation is also moving the sector forward; for example, machine learning-based monitoring systems are being developed to support rearing management and quality control at scale [13]. Research so far has revealed both opportunities and limits. Promising avenues include the economic use of co-products, the development of bioactive compounds, and socio-economic gains. However, these coexist with hurdles such as variable frass composition [14], allergenic risks [15], and uneven consumer acceptance [5]. A global synthesis confirms strong regional contrasts in acceptance and willingness to pay, with higher uptake in Africa, Asia and Latin America and stronger psychological barriers in Western contexts [16]. Recent reviews also argue that insect-based foods are unlikely to significantly displace meat consumption at scale in the near term, mainly due to persistent acceptance barriers and limited market momentum [17]. These bottlenecks are reviewed in detail elsewhere [18]. Objectives and scope: this review synthesizes peer-reviewed evidence published between 2020 and 2025, a period that coincides with rapid growth in industrial deployment, expanded regulatory approvals, and diversification of applications for *T. molitor*. Earlier foundational work is acknowledged but lies outside this update. We map key advances across food, feed, and co-products, and focus on key sustainability constraints that condition scale-up, including energy demand, water and substrate constraints, frass variability, allergenicity, and consumer acceptance. We also discuss how these constraints manifest across production contexts, including decentralized low-input systems relevant to arid regions.

2. Regulatory Framework and Legitimacy

This section reviews the regulatory and safety conditions that most directly shape the deployment of *T. molitor* in food and feed systems. Rather than serving as extended background, it focuses on the constraints most relevant to implementation and scale-up, including authorization, market access, contaminant control, allergenicity, and quality monitoring.

2.1. Regulatory Landscape and Approvals

The regulatory status of *T. molitor* has progressed markedly in recent years, especially in Europe. Since 2021, the European Union has authorized processed insect proteins for use in poultry and pig feed [19]. In parallel, EFSA concluded that frozen and dried whole *T. molitor* larvae are safe as a Novel Food under defined specifications and labelling requirements, and this position was reaffirmed in a later opinion [15,20]. In January 2025, the European Commission further extended this framework by authorizing UV-treated whole mealworm powder for use in processed foods [21]. Regulatory development is also advancing outside Europe, although unevenly. In Asia, initiatives supported by FAO Korea Partnership have contributed to regional discussions on edible insect regulation and harmonization [22]. For implementation, the main issue is not only authorization itself, but also the conditions attached to it. Regulation (EU) 2015/2283 provides the legal basis for Novel Food authorization, including transitional measures for products already lawfully marketed before EU-wide decisions [23]. In practice, labelling, traceability, product specifications, and market-access requirements directly affect commercialization and scale-up, even when technical feasibility has already been established [24].

2.2. *Safety, Toxicology, and Allergenicity*

Safety remains a central condition for the broader use of *T. molitor*. Available evidence shows that substrate composition can directly influence contaminant profiles, including heavy metal accumulation, making substrate selection and monitoring critical [25]. Toxicological studies are generally reassuring under the tested conditions, but longer-term datasets remain limited, especially for endpoints beyond short sub-chronic exposure [26]. EFSA safety assessments also emphasize processing, stability, microbiological criteria, and labelling as part of the overall suitability framework for food use [15,20]. Microbiological quality is another practical constraint. Properly processed batches can meet acceptable microbiological standards under Hazard Analysis and Critical Control Points (HACCP) monitoring, but this depends on reproducible processing and batch control [27]. From a scale-up perspective, this makes safety an operational issue as much as a biological one.

Allergenicity remains a major constraint for implementation. Current evidence shows sensitization and cross-reactivity risks, especially with crustaceans and mites. This supports the need for clear labelling and cautious risk communication [28,29]. Sensitization, however, does not necessarily predict clinical allergy, and oral food challenge data remain limited, although clinical reactions to insect ingestion have been documented [28,30]. More broadly, regulation and safety directly shape the scalability of *T. molitor* production, as well as the conditions required for traceability, quality control, and market acceptance.

3. Cost and Environmental Impact

The economic viability of *T. molitor* production depends largely on two interlinked factors: (1) feedstock cost efficiency and (2) regional resource availability [31]. These parameters shape both the operational strategy and the long-term sustainability of production systems, regardless of scale.

3.1. *Environmental Performance and Circularity*

In recent years, several investigations have shown that *T. molitor* farming, when embedded within circular agri-food systems, can cut environmental impacts while still generating outputs of economic value. Among these outputs, frass stands out. Analyses report nitrogen levels between 2.8 % and 4.1 %, phosphorus (P_2O_5) from 1.5 % to 2.4 %, and potassium (K_2O) ranging from 1.4 % to 2.0 %, together with a range of beneficial microorganisms [14]. This composition makes frass a valuable organic fertilizer, able to promote plant growth and support soil microbial communities. To achieve consistent agronomic benefits, nutrient ratios may need to be adjusted to the needs of each crop, while also meeting EU contaminant limits for heavy metals and other hazards.

The choice of substrate plays a major role in environmental performance. Life-cycle assessments show that agro-industrial by-products, including malt residual pellets, wheat bran, or corn germ meal, help sustain high larval yields and close nutrient cycles [32,33]. Lienhard and co-authors reported that malt residues matched the growth performance of wheat bran while making productive use of a local waste stream [33]. Such substitutions can reduce carbon emissions by up to 50 % and cut water use by 40-60 % compared with conventional fishmeal production [6]. Similarly, an Austrian life-cycle assessment found that while heating drives most of the climate burden, *T. molitor* still outperformed organic broiler across nearly all impact categories [2]. Production scale is another determining factor. Small, low-tech farms, often relying on manual operation, can function with much lower energy requirements than fully automated industrial plants. These decentralized approaches can be well-suited to areas with limited resources, provided that strict biosecurity and quality standards are maintained to ensure consistent outputs [34,35]. Nevertheless, Table 1 reveals that small-scale labour costs (8-12 hrs/kg) negatively impact the Return on Investment (ROI) in high-wage areas, favouring automated systems [35]. Economic analyses suggest that integrating frass upcycling into the production chain can also improve environmental metrics. For example, in Dutch models, such integration was estimated to offset 20 % to 25 % of operational costs while simultaneously reducing the overall ecological footprint [27,36]. Policy incentives like EU tax breaks could help industrial systems overcome nutrient loop challenges while boosting circularity [36]. In this review, the “low-tech” column reflects an arid-zone low-input production model: scarce water, wide day/night temperatures, and irregular substrates. Practical adaptations are simple: passive ventilation, only essential evaporative cooling, and strict substrate screening. These constraints help explain higher labour inputs and the variability seen for growth and frass.

As summarized in Table 1, small-scale systems excel in circularity but face scalability trade-offs, whereas industrial production prioritizes consistency at higher energy costs. This contrast is not only about scale but also geography. Small-scale, low-tech systems often match the realities of arid regions, where energy is costly and water is scarce. Local residues, like downgraded fruits or crop by-products, become the main resource. In these contexts, the arid-zone low-input model is less about yield maximization and more about survival and resilience. Industrial farms, by contrast, depend on stable inputs and heavy infrastructure, which are rarely feasible in such environments. Here, “arid-zone low-input production” refers to decentralized, low-input rearing under water scarcity and large day/night temperature fluctuations, with minimal active climate control and reliance on locally available residues. Concrete examples discussed in this review include by-product-based diets (e.g., malt residues) [33], on-farm frass stabilization (e.g., rice hull blending) [37], and frass use as fertilizer in arid sandy soils [38].

Table 1. Sustainability constraints across *T. molitor* production contexts, contrasting small-scale/low-tech (arid-zone relevant) with industrial/large-scale approaches.

Parameter	Small-Scale Low-Tech (arid-zone relevant)	Industrial Large-Scale	Key Implications
Substrate	Local by-products (high variability) [37,39]	Standardized diets (consistent nutrients) [37]	Small farms adapt to waste but face contamination risks
Climate and humidity control	Minimal active control, passive ventilation, only essential cooling [33]	Heating, Ventilation and Air Conditioning (HVAC) with controlled temperature and humidity, year-round output [34]	Infrastructure intensity and energy demand vs robustness in constrained environments
Energy Use	15–20 kWh/kg (passive systems) [33]	25–30 kWh/kg (HVAC + automation) [34]	Industrial cuts labor costs but increases energy demand.
Labor	8–12 hrs/kg (manual processes) [34]	1–2 hrs/kg (automated) [34]	Critical for Return on Investment (ROI) in high-wage regions [35]
Monitoring and quality control	Lower instrumentation, relies on Standard Operating Procedures (SOPs) and substrate screening	Digital monitoring and automation support rearing management and quality control at scale [13]	Traceability and batch consistency vs cost and complexity
Frass Quality	Variable Nitrogen, Phosphorus, Potassium (NPK), occasional arsenic (As) exceedance [39]	Uniform NPK, European Food Safety Authority (EFSA) compliant [39]	Small-scale requires blending, e.g., rice hulls [37]
Circularity	High (local waste recycling) [33]	Moderate (logistics constraints) [36]	Policy incentives could boost industrial circularity [36]

Note: Data compiled from multiple sources [6,33,34,36]. Energy estimates exclude transport emissions for decentralized systems. The low-tech column is particularly relevant for arid-zone constraints (water scarcity, large diurnal temperature range, limited infrastructure).

3.2. Economic Feasibility and Production Models

The economic viability of *T. molitor* production depends largely on two factors: feedstock cost structures and the availability of local resources [31]. Controlled trials have shown that agricultural by-products such as malt pellets and corn germ meal can match the yields obtained with conventional wheat bran [33]. An illustrative observation from Biskra, Algeria, an arid-zone context, was reported by Debache (2021). In that study, larvae reared on downgraded local dates showed growth outcomes comparable to those obtained on vegetable scraps [40]. Because compositional measurements were not available, this example should be regarded as preliminary and interpreted cautiously.

In Europe, profitability depends above all on three factors. Feed conversion efficiency is the key driver. Labour productivity also matters but is often underestimated. Finally, the market value of insect proteins adds volatility that producers must manage [27,36,39]. Together, these factors explain why small-scale and industrial systems follow distinct economic paths. Small-scale operations often achieve financial stability sooner. Their reduced capital requirements and localized distribution networks shorten the path to breakeven. In contrast, industrial-scale production relies on substantial upfront investment but can deliver lower unit costs through economies of scale. Interestingly, such outcomes are more likely when policy support and adaptable business models are present [41].

The choice of production model ultimately reflects regional assets and constraints. Regions rich in agro-industrial residues but with limited capital tend to favour decentralized, low-tech approaches. In arid-zone settings, the cost structure shifts from electricity to labour and logistics. Consequently, decentralized hubs can remain viable where wages are low, even if biomass is scarce. In contrast, high-wage economies inevitably favour automated, large-scale systems. This framing helps clarify the arid-zone model as a distinct pathway within the broader spectrum of mealworm production systems. Capital-intensive environments, by contrast, lend themselves to automated vertical integration, though careful energy management becomes essential to control ongoing costs [34]. In these settings, gentle drying preserves lipids and vitamins. In practice, low-energy drying requires tighter time and temperature control and microbiological monitoring, including HACCP-based oversight for processed batches [42]. These low-tech adaptations are not just cost-driven but also context-specific, directly linking production models to territorial resilience. Dutch models suggest that profitability can be reached within three to five years when co-products such as oil and frass are fully valorised [36]

4. Nutritional Quality and Food Innovation Potential

It is now well established that *T. molitor* larvae are protein-rich, with values typically ranging from 44.2% to 60.2% of dry matter [42–44]. However, these concentrations should not be interpreted as uniformly higher than all conventional animal protein sources. What makes mealworm protein particularly valuable is its complete amino acid profile, with substantial amounts of lysine (K), leucine (L) and valine (V), similar to what we find in lean meats [44]. These proteins consist of both structural components like actin and myosin, and soluble fractions packed with essential amino acids. The lipid fraction is also of considerable interest, representing between 20.0% and 36.0% of dry matter [44]. In line with many other animal-derived sources, the fatty acid profile is largely shaped by polyunsaturated fats, with omega-6 linoleic acid making up 47-54% of total lipids. By contrast, omega-3 α-linolenic acid remains scarce (1.0-1.8%), which leads to an omega-6 to omega-3 ratio in the range of 25:1 to 35:1 [5,43]. The larvae further provide notable amounts of oleic acid (27-32%) and a saturated fraction (21-26%) dominated by palmitic acid at roughly 15% [44]. It should be noted that processing may influence these qualities. Lipid stability can decline over time, and drying steps may accelerate this effect. Heat during processing can also destroy certain vitamins. Microbiological safety considerations are addressed in Section 2.2. Here, we only note that processing and monitoring can support compliance with microbiological criteria for food batches [42]. Recent innovations have successfully incorporated *T. molitor* into various food products, as highlighted in the comprehensive review by Kotsou and collaborators [18]. The applications range from protein-packed snacks to pasta and bakery items. Food technologists are addressing sensory challenges through fine milling, flavor masking, and blending with familiar ingredients [18]. In bakery applications, *T. molitor* larval powder replacing 5-10% of wheat flour increases water absorption (+4-6%) and improves mixing stability. The resulting breads show greater volume and a softer crumb; above ~15% substitution, crumb darkening and roasted notes intensify. A practical mitigation is protease pre-treatment, which improves gas retention and helps maintain texture [45]. In a study tracking composition across larval instars, later instars reached up to 56% protein (dry matter) and showed high levels of leucine, lysine, and valine. Earlier instars contained more polyunsaturated fats, while later instars accumulated a higher proportion of monounsaturated oleic acid [46]. For producers, this suggests that harvest timing may be adjusted either to maximize protein yield or to target a specific fatty acid profile, depending on the intended application. In arid contexts, later-instar harvests can help prioritize protein when cooling is limited. The next section shifts from composition to evidence in animal feed.

5. Applications in Animal Nutrition

The meal and oil derived from *T. molitor* are increasingly studied for their potential in animal feed, particularly for monogastric species (poultry, pigs, fish). This section explores recent scientific findings regarding the use of *T. molitor* in these species, highlighting zootechnical, digestive, and health-related benefits. Two subsections are dedicated to the main sectors concerned: poultry and other monogastrics.

5.1. Poultry (Broilers, Quails)

Several authors have reported that incorporating *T. molitor* into poultry diets delivers clear nutritional benefits [47,48]. Studies using inclusion levels as low as 5-10 % have still shown measurable gains in growth and feed efficiency [48–50]. In slow-growing chickens, full replacement of soybean meal with *T. molitor* can reduce feed intake and early growth. Performance, however, converged by ~95 days, with final outcomes comparable to conventional diets [47]. Biasato and colleagues evaluated *Hermetia illucens* meal, *T. molitor* meal, and a 1:1 mixture of both meals in broiler diets at 5% and 10% inclusion. In that study, the 5% *T. molitor* diet improved feed efficiency relative to the control. However, as results from mixed-insect diets are study-specific, they are not used here to support conclusions on mealworm meal alone [51]. In addition, Japanese quail fed graded inclusion levels of *T. molitor* meal showed slight changes in performance and carcass traits. The authors concluded that inclusion levels above 1.65% slightly impaired growth performance [52]. From a market perspective, poultry stands out as the most widely consumed and culturally accepted monogastric worldwide. It faces fewer religious restrictions than pork. It also requires less water and infrastructure than aquaculture. All these factors keep poultry in a leading position as the prime target for insect-based feed innovations.

5.2. Other Monogastrics (Pigs, Fish)

Mealworm larvae protein shows high in vitro digestibility (91-99%) and good-to-excellent protein quality as determined by in vitro DIAAS (Digestible Indispensable Amino Acid Score, a measure of protein quality based on the digestibility of each indispensable amino acid) values of 89-92, comparable to high-grade animal proteins such as poultry or fish meal [53]. These profiles include approximately 6.5 % lysine and 2.1 % methionine (of crude protein), both key amino acids for post-weaning piglets. In addition, *T. molitor* meal has been assessed in growing pigs using integrated transcriptomics, metabolomics, and lipidomics [54]. This study reports diet-associated metabolic effects and changes in plasma metabolite profiles, providing a detailed evaluation beyond basic performance endpoints. Moreover, in post-weaning pigs, replacing fishmeal with 10% *T. molitor* meal over a 42-day trial resulted in overall average daily gains of approximately 0.39 to 0.40 kg/day and feed conversion ratio (FCR) values around 2.05 to 2.17, with final body weights comparable across groups. Hematological parameters and most biochemical indices were not affected, although cholesterol was modified [55].

In aquaculture, *T. molitor* has been widely tested as a sustainable replacement for fishmeal. In Nile tilapia, both partial and total substitution achieved growth rates and feed efficiency equal to, and sometimes exceeding, those from fishmeal diets, with average gains of 1.2-1.4 g/day and feed conversion ratio (FCR) values in the 1.3-1.4 range [6]. Fillet lipid profiles also shifted towards a higher proportion of polyunsaturated fatty acids [6]. Similarly, in rainbow trout, partially defatted *T. molitor* meal replacing fishmeal up to 100% (corresponding to 20% dietary inclusion) did not affect growth performance, and feed conversion ratio (FCR) values remained within a similar range across treatments [56]. The next section examines bioactive compounds and functional ingredients.

6. Bioactive Compounds and Human Health Applications

Recent work increasingly links the nutritional value of *T. molitor* to hydrolysates, peptides, and lipid fractions with potential functional properties. However, the current evidence base remains predominantly preclinical. Most reported effects derive from in vitro assays, supported in some cases by animal models, whereas controlled human validation is still lacking. This section therefore focuses on the main functional categories emerging from recent studies and distinguishes between established observations, promising applications, and current translational limits. Protein hydrolysates from *T. molitor* consistently show antioxidant and anti-inflammatory potential in vitro. Controlled hydrolysis and simulated gastrointestinal digestion have generated low-molecular-weight peptide fractions with radical-scavenging activity and modulation of inflammatory markers in cell models, including reductions in TNF-α, IFN-γ, and IL-6 under stimulated conditions [57,58]. Recent syntheses further support the view that such fractions may provide promising functional food or nutraceutical leads [59,60]. Experimental studies using food-grade proteases likewise reported DPPH radical-scavenging and ferric-reducing activities, while structure–activity modelling suggests that amino acid composition may influence antioxidant potency [61,62]. Nevertheless, these findings remain strongly dependent on processing conditions, assay design, and peptide fractionation, and they do not yet demonstrate efficacy under realistic dietary exposure.

Cardiometabolic applications are also increasingly reported. Several studies identified *T. molitor*-derived peptides with angiotensin-converting enzyme inhibitory or dipeptidyl peptidase-IV inhibitory activity, suggesting possible relevance for blood pressure and postprandial glucose regulation [18,63–66]. Because dipeptidyl peptidase-IV degrades the incretin hormones GLP-1 and GIP, inhibition of this enzyme is mechanistically relevant to postprandial glucose regulation [67]. In animal models, defatted larval extracts or selected peptide fractions were associated with antihypertensive and cardioprotective effects, including reductions in systolic blood pressure and improvements in selected oxidative and inflammatory markers [63,68]. These results are promising, but translation remains preliminary because bioavailability, effective dose, pharmacokinetics, and long-term safety in humans remain insufficiently characterized.

More exploratory evidence concerns neuroprotective and dermocosmetic applications. A recent mouse study reported improved cognitive readouts after administration of an extract containing *T. molitor*-derived material [69]. Other studies described moisturizing, cytoprotective, or anti-inflammatory effects relevant to skin care and dermatitis models, including peptide-based dermocosmetic perspectives, trypsin hydrolysates active in vivo, and topical applications of mealworm oil [70–72]. At present, however, these applications should be considered emerging rather than established, because the evidence is still limited to experimental models and early formulation studies.

Overall, the literature supports *T. molitor* as a promising source of bioactive fractions, but the current evidence remains uneven across applications and is largely preclinical. For clarity and to avoid overinterpretation, specific peptide sequences and compound-level details are retained in Table 2, while the main text emphasizes evidence strength and translational constraints. Future work should prioritize standardized processing pipelines, reproducible characterization of active fractions, bioavailability studies, and controlled human trials before strong health claims are advanced.

Table 2. Bioactive compounds from *T. molitor* and their reported health effects. AA = amino acids; YAN = Tyrosine-Alanine-Asparagine; DPP-IV = dipeptidyl peptidase IV; GI = gastrointestinal; TLR = Toll-like receptor; MAPK = mitogen-activated protein kinase.

Bioactive Compound	Health Effect	Refs.
Cryptides (2–20 AA)	Antioxidant, anti-inflammatory	[57]
YAN	Antihypertensive	[63,65]
Hydrophobic fractions	Cardiovascular protection	[18]
LPDQWDWR, APPDGGFWEWGD	Type 2 diabetes	[64]
VVYPWTQ, AWYGANK, LWDHKV	Antihypertensive	[41]

Defatted larval extract	Cardioprotective, anti-inflammatory	[68]
DPP-IV inhibitors	Type 2 diabetes	[66]
Glycosides & heterocycles	Neuroprotective	[69]
Alcalase hydrolysates (standardized process)	Antioxidant; antimicrobial vs. *S. aureus*, *E. coli*	[58]
Food-grade protease	Antioxidant activity (DPPH, ferric-reducing)	[62]
WLNSKGGF, GFIPYEPFLKKMMA	Antimicrobial candidates prioritised in silico; validation pending	[73]
Protein hydrolysates (time-resolved)	Increasing antioxidant capacity during hydrolysis	[5]
Fermented hydrolysates (*L. plantarum*)	Anti-inflammatory; improved GI motility (mouse)	[74]
Phenolic compounds (methanolic extracts)	Antioxidant (DPPH, FRAP)	[75]
Dermocosmetic peptides (review)	Anti-ageing, moisturizing, soothing (skin)	[72]
Trypsin hydrolysates (in vivo, dermatitis)	Atopic dermatitis amelioration (TLR-MyD88-MAPK)	[70]
T. molitor oil (keratinocytes)	Moisturizing; cytoprotective for skin repair	[71]

Note: References compiled from multiple studies between 2020 and 2025; values indicate reported experimental outcomes under controlled conditions. These examples collectively highlight the potential of *T. molitor* proteins and extracts as functional ingredients in health-oriented applications.

7. Low-Tech Scalability & Biorefineries

7.1. Substrate Flexibility and Local Waste Streams

In this section, “arid-zone low-input production” is used as defined in Section 3.1. Low-tech *T. molitor* production offers a surprisingly adaptable solution for resource-limited regions. These resilient insects naturally tailor their growth to local conditions, as demonstrated by Shah and colleagues [31], who showed how larval development and body composition shift with dietary changes, essentially making the most of whatever food is available. This remarkable flexibility was also observed by Mahmoud and colleagues [34]. They reported distinct developmental patterns when switching between cereal byproducts and vegetable residues. In the same line, Greek researchers tested wheat bran, brewery spent grains, olive leaves, and mushroom waste, showing that larvae performed well on bran and spent grains, whereas other substrates gave inconsistent results [76]. To adapt rearing systems to local conditions, researchers have proposed simplified steps. Fondevila and colleagues demonstrated that tuning the starch-to-fiber ratio can significantly improve larval performance, making even low-quality residues more suitable for growth [77]. López-Gámez and collaborators observed that when dried vegetables or crop residues were added, the larvae found the diet more palatable. This adjustment also increased protein yield and improved nutrient availability [49]. In another trial, Yakti and colleagues tested bean and strawberry vegetative wastes. They applied simple pre-treatments such as autoclaving and solid-state fermentation with *Trichoderma reesei*. Results were mixed. Autoclaved bean residues maintained larval yields and enriched the biomass with minerals like calcium and iron. In contrast, strawberry residues, whether raw or pretreated, reduced larval performance. Still, they improved micronutrient content (e.g., manganese, zinc, iron). Overall, bean residues supported larval performance more consistently than strawberry residues. The key message is that even modest processing can strongly change both growth outcomes and nutritional profiles [78]. Taken together, these studies suggest that locally available residues can support *T. molitor* rearing under constrained conditions, although performance remains strongly substrate-dependent. Finally, resource loops can close directly on-farm. In arid sandy soils, the application of *T. molitor* frass produced clear effects. Lettuce and tomato biomass increased by 20-28%, linked to higher foliar nitrogen and potassium levels that supported stronger plant growth [38]. Compared with a conventional mineral fertilizer, frass often achieved similar or even superior results. The benefit extended beyond yields, since soil microbial stability was also maintained, confirming the multifunctional role of frass within low-tech rearing systems. Scalability and socio-economic feasibility in low-input settings ultimately depend on labour costs, residue availability, minimal processing capacity, and the ability to maintain basic biosecurity and traceability.

7.2. Frass and Co-Product Valorisation

As previously outlined (see Section 3.1), frass nutrient values vary considerably with substrate and rearing conditions. Zunzunegui and co-authors reported ≈ 4.5 % N, 2.6 % P, and 2.5 % K, together with calcium (~2.4 %), magnesium (~0.8 %), and trace elements such as Zn, Cu, and Fe. They also suggested that residual chitin fragments may stimulate beneficial soil microorganisms. In greenhouse tomato trials, the same material provided not only a solid nutrient supply but also a clear biostimulant-like boost [14]. However, Lopes and colleagues caution that this composition is highly variable, shifting considerably with the original substrate and processing conditions, and point out that “frass” can include insect excreta, uneaten feed, larval cuticles and associated microbes. As a result, results differ across studies, and harmonised analytical protocols are needed [79]. Still, outcomes remain inconsistent. This is not surprising, given the mix of materials involved. Before strong biostimulant claims can be made, reproducibility and standardization must come first. Alternative routes have also been explored. Through solid-state fermentation, Aspergillus oryzae produced protease activities around 350-400 U/g when frass humidity was near ~ 65 %; activity remained stable for several days [80]. In parallel, anaerobic digestion studies reported biogas outputs of 44-668 m^3 ton^{-1} VS and methane yields of 26-502 m^3 ton^{-1} VS, placing them within the range of livestock manures [81]. In that study, performance depended on feedstock mix, operating conditions, and co-digestion strategies. A distinct environmental application comes from He and collaborators carbonising *T. molitor* frass yielded an Fe-loaded biochar catalyst (Fe/FBC; surface area 90.65 m^2/g; Fe(III) 6.0 %). In a photo-assisted Fenton-like process, the catalyst removed 67 % of total organic carbon from malachite-green dye in ~ 5 min and remained stable over reuse cycles. The main pathways involved N-demethylation, hydroxylation and chromophore disruption. Life-cycle analysis indicated lower impacts than standard composting, notably for climate change, aquatic toxicity and eutrophication [82].

In parallel, integrated biorefinery concepts underline the complementarity between insect rearing and co-product recovery. Oil fractions, protein hydrolysates and residual frass can be channelled into food, feed or energy loops [83]. Within this framework, protein hydrolysates surpassed 72% protein while demonstrating valuable emulsifying, foaming, and antioxidant capabilities. Similar high protein levels have been reported in other studies. Some hydrolysates even exceeded 70% protein, showing potential for food and nutraceutical applications due to their emulsifying and antioxidant properties [5,31,45]. For example, Chewaka and co-authors used nuruk extract to obtain very small peptides (< 1 kDa) reaching 71.6% protein, all while keeping their key functional properties [8].

7.3. Systemic Integration and Biorefinery Models

Several technical innovations aim to optimize resource recovery within circular systems. Kröncke and colleagues developed a zigzag air separator for larval isolation, combined with image-based neural networks for quality control. The same work noted that drying duration and temperature directly affect nutritional profiles. Oil extraction by screw pressing, followed by conversion of the press cake into insect meal using rolling mills, produced a feed comparable to fishmeal [46].

Moruzzo and colleagues emphasized in their review that *T. molitor* acts as a central agent in circular food and agriculture systems, turning diverse residues into proteins, lipids, chitosan, or biofertilizers [84]. Despite this potential, structural bottlenecks persist. Substrate logistics, lack of product standards, and consumer acceptability limit expansion. Vodenicharova (2023) added that in Europe, the absence of harmonized supply chain strategies, across pre-sale, on-sale, and post-sale stages, remains a major obstacle [85]. Recent work also points to hybrid biorefineries combining insect co-products with bioenergy production. Anaerobic digestion or biogas generation from frass and side-streams can provide both material and energetic returns, situating *T. molitor* within broader resource recovery frameworks [83].

8. Agroecological and Biotechnological Synergies (2020-2025): Towards a Circular Bioeconomy

T. molitor is now recognized as a flexible organism positioned between agroecology, biotechnology, and circular economy practices. Studies from the past five years show its use in waste recovery, the design of new biomaterials, and its integration into sustainable food and industrial systems. *Unlike Section 6, which focuses on direct human health applications of bioactive compounds, this section emphasizes technological, agro-industrial, and cross-sectoral developments.*

8.1. Cross-Sector Innovations and Integrated Applications

Recent work has expanded the upcycling of *T. molitor* beyond its nutritional potential toward biopolymers, oils, and system-wide applications. High-tech urban models such as vertical farming consolidate production in controlled environments using LEDs, sensors and automation, but raise energy-efficiency constraints [35]. Chitosan has been obtained from discarded larvae and exuviae, with yields close to those reported for marine sources. This insect-derived material shows reduced allergenic risk and a smaller environmental footprint [86–88]. One study reported antibacterial effects of insect chitosan against *Pseudomonas aeruginosa*, pointing to possible agro-industrial and biomedical uses [89]. New technologies are also streamlining protein processing. For example, Perez and collaborators used pulsed electric fields to boost protein recovery from mealworm flour. This method improved foaming properties without changing its nutritional value. Such non-thermal methods expand the functional applications of insect proteins in food and industrial formulations [90].

The oil fraction of *T. molitor* offers further technological opportunities. Martínez-Pineda and co-authors found that the oil contained about 43% oleic acid and 33% linoleic acid. γ-tocopherol and sterols were also identified. The extract showed high oxidative stability [91]. Furthermore, in food applications, South Korean studies [92,93] demonstrated that this oil can be blended with natural waxes to form stable oleogels. These oleogels successfully replaced shortening in bakery products, with no loss of quality. Larvae of *T. molitor* are able to consume many types of agro-industrial residues. For example, studies mention brewery by-products, cassava peels, date pits, and other side streams [40,49,77]. In addition, dairy by-products such as mozzarella whey and whey permeate have been successfully upcycled, with larvae showing increased protein content (≈ +7 %) and favourable fat composition [94]. On their own, such inputs have almost no commercial value. Yet the larvae manage to turn them into protein- and lipid-rich biomass. This process also significantly helps to lower rearing costs for producers. At present, most of these outputs remain at pilot scale. Oil, peptides or oleogels are produced in hundreds of kilos, rarely in tonnes. The near-term value lies in niche applications and full recovery of co-products, not in replacing bulk commodities. Frass, the coproduct of this activity, has been studied on its own. Zunzunegui and colleagues highlighted how leftover chitin fragments can stimulate soil microorganisms, which indirectly supports plant growth [14]. Interestingly, Muñoz-Seijas and collaborators placed frass within a biorefinery perspective. In that context, adding it to anaerobic digesters was linked with higher biogas yields [83].

In addition to organic waste, larvae can also process synthetic materials. This capacity for plastic biodegradation is mediated by their gut microbiota. Metagenomic studies by Mamtimin and colleagues revealed that *T. molitor* larvae fed with polystyrene harbor microbial consortia. These communities were dominated by Exiguobacterium and Pseudomonas, both known for polymer decomposition [95]. Nutritional co-substrates such as lysine and methionine further enhance degradation efficiency [96]. Enzymes such as feruloyl esterase-like PETases isolated from larvae confirm the direct enzymatic potential of this system [97]. Yet efficiency remains limited, and degradation rates are slow compared to industrial recycling. The potential for generating secondary microplastics remains an open question. For now, these efficiency and safety constraints limit the large-scale relevance of this process. Notably, bioinformatics is now contributing to this field as well. Recent work on the *T. molitor* proteome has identified cuticular proteins as promising precursors of bioactive peptides, particularly DPP-IV inhibitors [98]. Although mainly discussed in health contexts, such in silico tools may also be adapted to predict functional traits of insect proteins and, by extension, support agro-industrial applications. In a separate but equally critical line of research, several teams have investigated how plant secondary metabolites interfere with insect physiology. This is a key consideration when using agricultural residues as feed. For instance, larvae of *T. molitor* exposed to high doses of the mycotoxin zearalenone showed weakened antioxidant defences and even a loss of locomotor activity [99]. A similar outcome was noted when phytochemicals forced *T. molitor* to reshape its digestive and detoxification enzymes, which required adjustments in its enzymatic toolkit [100]. More recently, Winkiel and colleagues showed that Solanaceae glycoalkaloids modulate energy metabolism in *T. molitor*, affecting glycolysis (phosphofructokinase, PFK), the TCA cycle (citrate synthase, CS), and β-oxidation (3-hydroxyacyl-CoA dehydrogenase, HADH) [101]. In a companion study, Winkiel and co-authors showed disruptions in lipid metabolism, with altered triacylglycerols and a drop in 3-hydroxyacyl-CoA dehydrogenase activity in the fat body [102]. *In addition to glycoalkaloids, essential-oil volatiles such as (E)-2-decenal, furfural, 2-undecanone and (E,E)-2,4-decadienal impaired T. molitor reproduction in vivo. They reduced terminal oocyte size, vitellogenin expression and follicular patency, cutting oviposition by ~33–43% with lower hatchability; at* 10^{-5} *M, (E)-2-decenal also lowered female survival to ~39%* [103]. In broilers, Biasato and colleagues found that including 5% *Tenebrio molitor* (TM) or a 1:1 blend of *Hermetia illucens* (HI) and *T. molitor* (TM) improved feed efficiency and carcass weight, whereas 10% HI or a 10% HI-TM blend yielded the weakest outcomes; meat-quality effects were variable [51]. *In that study, feed conversion improved and intestinal morphology showed favourable changes* [51]. Additional work has explored effects on gut health. Interestingly, ingredients derived from *T. molitor* were shown to modulate the microbiota and to enhance immune responses in monogastric animals [104]. This places insect rearing within a wider perspective of livestock health and welfare, suggesting that it can contribute to One Health approaches.

8.2. Biotechnologies and Innovative Materials

Applications of *T. molitor*-derived biomolecules extend into material sciences. Chitosan-based packaging films and coatings have demonstrated enhanced barrier properties, antimicrobial activity, and fruit preservation capacities [105–107]. These biodegradable solutions represent sustainable alternatives to petrochemical plastics. Microbiota-assisted biodegradation further broadens the portfolio of green biotechnologies. Mixed diets combining plastics and organic substrates modulate gut microbial communities toward polymer-degrading taxa [108], while co-feeding strategies improve larval survival under otherwise suboptimal diets [109]. Biomedical research has also leveraged *T. molitor* chitosan for advanced materials. Nanofibrils and bioengineered chitin–lignin complexes show compatibility with extracellular matrices, supporting applications in tissue scaffolding, wound healing, and controlled release systems [4,110,111]. These results place insect-derived chitosan as a promising renewable resource for next-generation biomaterials. Notably, insights from non-insect models reinforce this perspective. A recent study on tilapia skin successfully isolated cytoprotective peptides and validated their function in silico, showing protection of ovarian granulosa cells against oxidative stress [112]. Such workflows, combining peptide isolation with computational validation, highlight transferable strategies that could equally enhance the biotechnological exploitation of *T. molitor*. Agroecological studies also point to synergies between insect-derived polymers and plant systems. For example, insect chitosan has been shown to trigger defence pathways in crops, offering a sustainable alternative to synthetic fungicides [43]. This aligns the use of *T. molitor* with integrated pest management strategies.

8.3. Modular Biorefineries and Territorial Modeling

Integrated biorefineries represent one of the most promising avenues for scaling *T. molitor*. In practice, no fraction of *T. molitor* is wasted. Primary products include protein flour, oils, and chitosan. Secondary outputs cover frass and bioinformatic data. These flows lead to urban fertilization, animal feed, and sustainable agriculture, as shown in Figure 1.

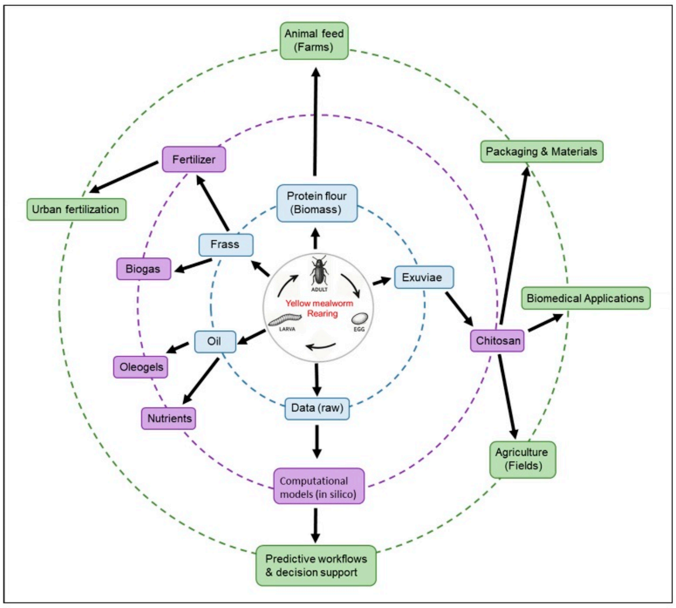

Figure 1. Integrated modular biorefinery for *T. molitor*. Center: rearing and life cycle. Ring 1: primary outputs (protein flour, oils, exuviae). Ring 2: intermediate valorisation (fertiliser, biogas, oleogels, chitosan, in-silico data). Outer nodes: territorial uses (urban fertilisation, animal feed, field crops, packaging/materials and biomedical). Arrows indicate transformation or use; no reverse flows are implied.

Case studies in France and the Netherlands demonstrate that combining insect farming, peptide extraction, and urban fertilization can achieve profitability within three years [36,83]. Techno-economic models point out that substrate costs (~1 939 €/t DM), capital expenditure (~1 459 €/t DM), and energy use (~693 €/t DM) remain the primary economic bottlenecks [36,113]. Life cycle assessments reveal lower greenhouse gas emissions and water use than conventional animal proteins, but also highlight non-renewable energy demand as a critical impact category [114,115]. This is consistent with an Austrian LCA of mealworm farming, which identified heating as a dominant hotspot while still outperforming organic broiler across most impact categories [2]. Comparative studies with other alternative proteins (e.g., Spirulina) show similar challenges of cost and scalability [116]. This has brought coproduct recycling and territorial integration into focus. Moreover, pilot projects indicate that the use of frass in agro-aquaculture systems supports nutrient recycling and reduces reliance on chemical fertilizers [5]. This demonstrates the capacity of *T. molitor* coproducts to contribute to climate-resilient territorial models. Beyond insects, predictive workflows developed for agro-industrial by products such as tomato residues have demonstrated the feasibility of identifying bioactive peptides entirely in silico [117]. Transferring such computational approaches to *T. molitor* could enhance integrated biorefineries, enabling not only the extraction of proteins and lipids but also the conversion of secondary flows in a circular economy framework.

8.4. Challenges and Prospects for Sustainable Industrialization

Scaling *T. molitor* production faces systemic barriers. Maintaining a steady supply of substrates remains a challenge. Energy efficiency is another unresolved issue, and seasonal variations still complicate production. Nevertheless, LCAs consistently flag non-renewable energy demand, largely from heating, as the dominant hotspot; the Austrian study confirms this even though mealworms still compare favourably to poultry systems [2]. Importantly, in slow-growing animals, full soybean replacement is not performance-neutral during early phases [47]. Plant secondary metabolites, especially Solanaceae glycoalkaloids, can blunt energy metabolism and disrupt lipid handling in *T. molitor*, likely contributing to the performance variability seen on plant-residue diets [101,102]. Environmental concerns also enter into the picture. One relates to competition with other industries for feedstock. Another is the ecological risk that could occur if insects escape and establish themselves in non-native ecosystems. Social acceptance continues to constrain expansion. Consumer surveys indicate greater acceptance of flours and processed forms than of whole insects [5,53].

Camouflaged or blended ingredients, combined with transparent communication and traceability, appear critical for improving adoption. Regulatory frameworks are progressing unevenly. While EFSA approvals in Europe are expanding [15,20], other regions such as Africa lack harmonized standards despite traditional entomophagy practices [22]. Asia presents a mixed picture, with countries like South Korea moving faster than others [118]. Harmonized safety and labelling protocols will be essential for global trade.

8.5. Perspectives for Innovative Applications

In addition to the domain-specific applications detailed in Table 3, recent years have seen the emergence of transversal bioinformatic workflows and predictive in silico pipelines. These tools facilitate the discovery of novel bioactive peptides in *T. molitor*. Moreover, they provide transferable methodologies that can be applied to other organisms and by-products. This dual capability reinforces the systemic integration of insect biotechnology into a circular bioeconomy.

Table 3 provides a synthetic overview of these promising cross-sectoral opportunities identified between 2020 and 2025. Note that rows focused solely on human nutraceutical peptides (e.g., antihypertensive agents, DPP-IV inhibitors) have been excluded, as they are discussed in depth in Section 6. It is important to note that while Table 3 effectively highlights sectoral opportunities and functional benefits, it does not convey their environmental footprint. To provide this crucial perspective, Figure 2 contrasts the life cycle impacts of mealworm production with a conventional protein source, using data from recent LCA studies [114,115]. When considered together, Table 3 and Figure 2 offer a comprehensive view of both the industrial potential and the ecological positioning of *T. molitor* valorisation.

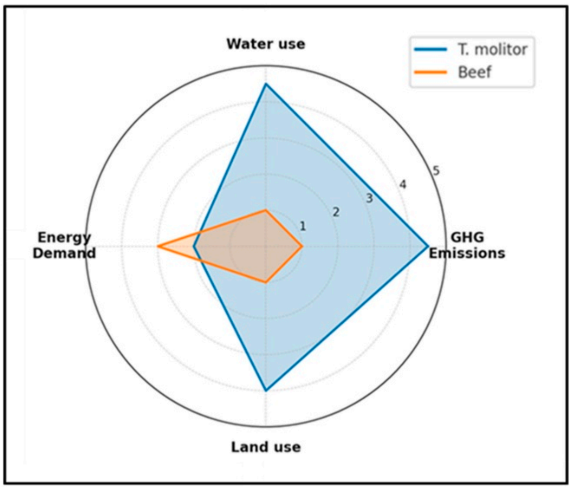

Figure 2. Comparative environmental performance of *T. molitor* and beef (illustrative). Radar diagram based on life cycle assessment (LCA) results. Axes cover greenhouse gas (GHG) emissions, water use, energy demand, and land use. *T. molitor* shows lower impacts in GHG emissions, water, and land use, while energy demand remains a relative weakness. Scores are normalized (1 = highest impact, 5 = lowest impact), so higher values indicate better environmental performance. Values are indicative, derived from published LCA studies [12,114].

Table 3. Summary of major application domains, opportunities, key constraints, and research gaps for *T. molitor*.

Domain	**Opportunity**	**Constraints**	**Research gaps**	**Refs.**
Animal feed	Most deployment-ready application, with promising results in poultry, pigs, and fish.	Batch consistency, substrate quality, and species-specific formulation.	Longer-term trials, field validation, and standardized inclusion thresholds.	[47,48,50–56]
Food innovation	Powders, breads, snacks, and oleogels broaden food applications.	Sensory acceptance, allergenicity, and processing-related variability.	Realistic inclusion rates, shelf life, nutritional stability, and consumer acceptance.	[45,91–93]
Bioactive fractions	Peptides and hydrolysates show antioxidant, anti-inflammatory, antihypertensive, and DPP-IV inhibitory potential.	Evidence remains largely preclinical, with limited bioavailability data.	Standardized processing, pharmacokinetics, and controlled human trials.	[57–60,62–66,68–72,74,75]
Frass and agricultural valorisation	Frass can support fertilization, biostimulation, digestion, and biochar production.	Composition varies with substrate and processing, and definitions remain inconsistent.	Harmonized definitions, field validation, contaminant benchmarks, and regulatory alignment.	[14,79–81,119]
Chitin, chitosan, and biomaterials	Insect-derived polymers show promise for packaging, antimicrobial films, and biomaterials.	Extraction routes, standardization, and scale-up remain limiting factors.	Process optimization, comparative performance, and industrial validation.	[4,86–89,105–107,110,111]
Low-input and arid-zone systems	Local residues may support rearing in resource-constrained settings.	High variability, labour intensity, limited monitoring, and still limited evidence.	Replicated field studies, standardized low-input protocols, and techno-economic validation.	[33,40,76–78,119]
Integrated biorefineries	Proteins, oils, frass, and side-streams can be valorised within circular systems.	Capital costs, energy demand, logistics, and traceability bottlenecks.	Integrated life-cycle assessment, techno-economic validation, and territorial implementation models.	[36,83,113–115,117]
Predictive workflows	In silico discovery and biodegradation-related tools may widen future applications.	Predictions still require validation, and biodegradation remains slow and safety-sensitive.	Mechanistic studies, experimental confirmation, and better scale assessment.	[73,98,112,117]

Note. This table synthesizes the main application domains discussed in this review and highlights their current opportunities, key constraints, and principal research gaps. Human nutraceutical applications are discussed separately in Section 6. Key references are provided as representative examples rather than an exhaustive list.

Conclusion

Across the 2020–2025 evidence synthesised here, *T. molitor* emerges as a versatile resource for circular bioeconomy strategies. It can convert diverse residues into proteins, lipids, chitin-derived materials, and frass, supporting applications in feed, food innovation, and co-product valorisation. Among these applications, feed appears the most deployment-ready, provided that diet formulation, hygiene, and batch consistency are properly controlled. Chitin-derived materials also show clear potential for biomaterial and dermocosmetic applications. By contrast, most reported bioactivities linked to food and functional ingredients remain preclinical. Many findings are based on in vitro assays or short-term animal models, often under conditions that are not directly translatable to realistic dietary exposure. Their practical relevance therefore depends on standardized processing, robust safety and quality control, and stronger evidence on bioavailability and efficacy in controlled human studies. A central constraint across the literature remains reproducibility. Results vary with substrate choice, processing conditions, and analytical methods. This limits comparability across studies and weakens the strength of some health or agricultural claims. Sustainability outcomes also reflect a clear trade-off. Industrial systems provide greater consistency and traceability, but they require more infrastructure, process control, and compliance capacity. Low-input systems may fit arid and resource-constrained settings, but they remain more exposed to variability, labour constraints, and standardisation limits.

Overall, *T. molitor* is a credible component of the circular bioeconomy, but its long-term impact will depend on realistic positioning and stronger methodological consistency. The sector is ready to scale selectively in applications where quality control, traceability, and markets are already aligned. Broader claims, especially for health-related applications or low-input deployment models, still require stronger standardisation and validation.

Author Contributions: The author was solely responsible for conceptualisation, investigation and writing (original draft and review/editing) of this manuscript.

Funding: This research was self-funded by the author and received no external funding from public, commercial, or non-profit sources.

Data, Script and Code Availability: This review relies on published literature. No new datasets, statistical scripts, command lines, or simulation code were generated. All sources are cited in the reference list.

Acknowledgments: The author used AI-based tools to assist with reference management and style editing. All scientific content, data interpretation and conclusions are the sole responsibility of the author. A preprint version of this article has been peer-reviewed and recommended by PCI Anim Sci (https://doi.org/10.24072/pci.animsci.100388).

Conflicts of Interest Disclosure: The authors declare they have no conflict of interest relating to the content of this article.

Supplementary Information: No supplementary information is associated with this manuscript.

Materials and Methods: Literature scope and selection. This narrative review synthesizes peer-reviewed literature published between 2020 and 2025 on *Tenebrio molitor* in relation to food, feed, co-products, and circular bioeconomy applications. This time window was chosen to capture recent regulatory developments, industrial deployment, and the diversification of applied research in the field. Earlier landmark studies were cited selectively for context, but they were not the main focus of this update. Literature was included on the basis of its relevance to the review objectives, especially when studies addressed nutritional value, food and feed applications, safety and allergenicity, frass and co-product valorization, life-cycle assessment, and constraints affecting scale-up or low-input production contexts. Official regulatory and institutional sources were also used where needed to support legal or policy-related statements. This review was designed as a critical narrative synthesis and does not aim to provide an exhaustive systematic inventory of all publications on *T. molitor*.

References

1. Despommier D. Vertical farming: a holistic approach towards food security. Front Sci. 2024 Sep 24;2. doi:10.3389/fsci.2024.1473141
2. Dreyer M, Hörtenhuber S, Zollitsch W, Jäger H, Schaden LM, Gronauer A, et al. Environmental life cycle assessment of yellow mealworm (*Tenebrio molitor*) production for human consumption in Austria – a comparison of mealworm and broiler as protein source. Int J Life Cycle Assess. 2021 Nov;26(11):2232–47. doi:10.1007/s11367-021-01980-4
3. Khanal P, Pandey D, Næss G, Cabrita ARJ, Fonseca AJM, Maia MRG, et al. Yellow mealworms (Tenebrio molitor) as an alternative animal feed source: A comprehensive characterization of nutritional values and the larval gut microbiome. J Clean Prod. 2023 Feb;389:136104. doi:10.1016/j.jclepro.2023.136104
4. Marín-Morales MS, Ibarra-Herrera CC, Rivas-Arreola MJ. Obtention and Characterization of Chitosan from Exuviae of *Tenebrio molitor* and *Sphenarium purpurascens*. ACS Omega. 2025 Apr 29;10(16):17015–23. doi:10.1021/acsomega.5c01987
5. Maciejewska M, Dąbrowska A, Cano-Lamadrid M. Sustainable Protein Sources: Functional Analysis of Tenebrio molitor Hydrolysates and Attitudes of Consumers in Poland and Spain Toward Insect-Based Foods. Foods. 2025 Jan 20;14(2):333. doi:10.3390/foods14020333
6. Khan MS, Parveen M, Saleem A, Bibi A, Sadaf N, Yousaf HK, et al. Mealworms (Tenebrio molitor L.) as a Substituent of Protein Source for Fisheries and Aquaculture: A Mini Review: Mealworms as a Substituent of Protein Source. MARKHOR J Zool. 2025 Mar 31;19–25. doi:10.54393/mjz.v6i1.134
7. Tlak Gajger I, Dar SA. Plant Allelochemicals as Sources of Insecticides. Insects. 2021 Feb 24;12(3):189. doi:10.3390/insects12030189
8. Chewaka LS, Park CS, Cha YS, Desta KT, Park BR. Enzymatic Hydrolysis of Tenebrio molitor (Mealworm) Using Nuruk Extract Concentrate and an Evaluation of Its Nutritional, Functional, and Sensory Properties. Foods. 2023 May 29;12(11):2188. doi:10.3390/foods12112188
9. Montalbán A, Martínez-Miró S, Schiavone A, Madrid J, Hernández F. Growth Performance, Diet Digestibility, and Chemical Composition of Mealworm (Tenebrio molitor L.) Fed Agricultural By-Products. Insects. 2023 Oct 20;14(10):824. doi:10.3390/insects14100824
10. Urbański A, Johnston P, Bittermann E, Keshavarz M, Paris V, Walkowiak-Nowicka K, et al. Tachykinin-related peptides modulate immune-gene expression in the mealworm beetle Tenebrio molitor L. Sci Rep. 2022 Oct 14;12(1):17277. doi:10.1038/s41598-022-21605-6
11. Food Standards Australia New Zealand. Edible insects as non-traditional food [Internet]. 2023 Dec. Report No. Available from: https://www.foodstandards.gov.au/sites/default/files/2023-12/Record-of-Views-updated-Dec-2023.pdf
12. Malila Y, Owolabi IO, Chotanaphuti T, Sakdibhornssup N, Elliott CT, Visessanguan W, et al. Current challenges of alternative proteins as future foods. Npj Sci Food. 2024 Aug 15;8(1):53. doi:10.1038/s41538-024-00291-w
13. Majewski P, Zapotoczny P, Lampa P, Burduk R, Reiner J. Multipurpose monitoring system for edible insect breeding based on machine learning. Sci Rep. 2022 May 12;12(1):7892. doi:10.1038/s41598-022-11794-5
14. Zunzunegui I, Martín-García J, Santamaría Ó, Poveda J. Analysis of yellow mealworm (Tenebrio molitor) frass as a resource for a sustainable agriculture in the current context of insect farming industry growth. J Clean Prod. 2024 Jul;460:142608. doi:10.1016/j.jclepro.2024.142608
15. EFSA Panel on Nutrition, Novel Foods and Food Allergens. Safety of frozen and dried formulations from whole yellow mealworm (Tenebrio molitor larva) as a novel food pursuant to Regulation (EU) 2015/2283 (EFSA 2021). EFSA J. 2021 Aug;19(8). doi:10.2903/j.efsa.2021.6778
16. Abro Z, Sibhatu KT, Fetene GM, Alemu MH, Tanga CM, Sevgan S, et al. Global review of consumer preferences and willingness to pay for edible insects and derived products. Glob Food Secur. 2025 Mar;44:100834. doi:10.1016/j.gfs.2025.100834
17. Biteau C, Bry-Chevalier T, Crummett D, Ryba R, Jules MSt. Beyond the buzz: insect-based foods are unlikely to significantly reduce meat consumption. Npj Sustain Agric. 2025 Jun 23;3(1):35. doi:10.1038/s44264-025-00075-z

18. Kotsou K, Chatzimitakos T, Athanasiadis V, Bozinou E, Athanassiou CG, Lalas SI. Innovative Applications of Tenebrio molitor Larvae in Food Product Development: A Comprehensive Review. Foods. 2023 Nov 22;12(23):4223. doi:10.3390/foods12234223
19. European Commission. Commission Regulation (EU) 2021/1372 of 17 August 2021 amending Annex IV to Regulation (EC) No 999/2001 as regards the prohibition to feed non-ruminant farmed animals, other than fur animals, with protein derived from animals [Internet]. Official Journal of the European Union; 2021. Available from: https://eur-lex.europa.eu/eli/reg/2021/1372/oj/eng
20. EFSA Panel on Nutrition and Novel Foods. Safety of frozen and dried forms of whole yellow mealworm (Tenebrio molitor larva) as a novel food pursuant to Regulation (EU) 2015/2283 (EFSA 2025). EFSA J. 2025 Jan;23(1). doi:10.2903/j.efsa.2025.9155
21. AGRINFO. Latest novel food authorisations – January 2025 [Internet]. COLEAD; 2025. Available from: https://agrinfo.eu/book-of-reports/latest-novel-food-authorisations-january-2025/
22. FAO Korea Partnership. FAO Korea Partnership Newsletter – 1st Quarter 2022, Issue #2 [Internet]. Food and Agriculture Organization of the United Nations (FAO); 2022. Available from: https://openknowledge.fao.org/items/66121641-98fb-4877-9e68-2b53b65ffa33
23. European Parliament. Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001 [Regulation] [Internet]. Strasbourg: Official Journal of the European Union; 2015 Nov. p. 1–22. Report No.: 2015/2283. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R2283
24. Żuk-Gołaszewska K, Gałęcki R, Obremski K, Smetana S, Figiel S, Gołaszewski J. Edible Insect Farming in the Context of the EU Regulations and Marketing—An Overview. Insects. 2022 May 7;13(5):446. doi:10.3390/insects13050446
25. Malematja E, Manyelo TG, Sebola NA, Kolobe SD, Mabelebele M. The accumulation of heavy metals in feeder insects and their impact on animal production. Sci Total Environ. 2023 Aug;885:163716. doi:10.1016/j.scitotenv.2023.163716
26. Machona O, Mutanga M, Chidzwondo F, Mangoyi R. Sub-chronic toxicity determination of powdered Tenebrio molitor larvae as a novel food source. Toxicol Rep. 2024 Jun;12:111–6. doi:10.1016/j.toxrep.2024.01.002
27. Niyonsaba HH, Höhler J, Kooistra J, Van Der Fels-Klerx HJ, Meuwissen MPM. Profitability of insect farms. J Insects Food Feed. 2021 Aug 13;7(5):923–34. doi:10.3920/JIFF2020.0087
28. Majsiak E, Choina M, Gromek W, Wykrota J, Kozłowska D, Swadźba J, et al. IgE-based analysis of sensitization and cross-reactivity to yellow mealworm and edible insect allergens before their widespread dietary introduction. Sci Rep. 2025 Jan 9;15(1). doi:10.1038/s41598-024-83645-4
29. Scala E, Abeni D, Villella V, VilIalta D, Cecchi L, Caprini E, et al. Investigating Sensitization to Novel Foods: A Real-Life Prevalence Study of IgE-Mediated Reactivity to Cricket, Locust, and Mealworm in Insect Food-Naïve Allergic Individuals. J Investig Allergol Clin Immunol. 2025 Jun 18;35(3):194–202. doi:10.18176/jiaci.0986
30. Garino C, Mielke H, Knüppel S, Selhorst T, Broll H, Braeuning A. Quantitative allergenicity risk assessment of food products containing yellow mealworm (Tenebrio molitor). Food Chem Toxicol. 2020 Aug;142:111460. doi:10.1016/j.fct.2020.111460
31. Shah AA, Usman A, Khan S, Khan F, Ahmed N, Al-Mekhlafi FA, et al. Mealworm (*Tenebrio molitor*) rearing and growth optimization as a sustainable food source using various larval diets under laboratory conditions. Entomol Exp Appl. 2024 Sep;172(9):827–36. doi:10.1111/eea.13463
32. Oh S, Lu C. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food security. J Hortic Sci Biotechnol. 2023 Mar 4;98(2):133–40. doi:10.1080/14620316.2022.2141666
33. Lienhard A, Rehorska R, Pöllinger-Zierler B, Mayer C, Grasser M, Berner S. Future Proteins: Sustainable Diets for Tenebrio molitor Rearing Composed of Food By-Products. Foods. 2023 Nov 11;12(22):4092. doi:10.3390/foods12224092

34. Mahmoud MA, Abotaleb AO, Zinhoum RA. Evaluation of various diets for improved growth, reproductive and nutritional value of the yellow mealworm, Tenebrio molitor L. Sci Rep. 2025 May 5;15(1). doi:10.1038/s41598-025-98254-y
35. Sowmya C, Anand M, Indu Rani C, Amuthaselvi G, Janaki P. Recent developments and inventive approaches in vertical farming. Front Sustain Food Syst. 2024 Sep 9;8. doi:10.3389/fsufs.2024.1400787
36. Niyonsaba HH, Groeneveld IL, Vermeij I, Höhler J, Van Der Fels-Klerx HJ, Meuwissen MPM. Profitability of insect production for T. molitor farms in The Netherlands. J Insects Food Feed. 2023 Dec 8;10(6):895–902. doi:10.1163/23524588-20230154
37. Noyens I, Schoeters F, Van Peer M, Berrens S, Goossens S, Van Miert S. The nutritional profile, mineral content and heavy metal uptake of yellow mealworm reared with supplementation of agricultural sidestreams. Sci Rep. 2023 Jul 18;13(1):11604. doi:10.1038/s41598-023-38747-w
38. Verardi A, Sangiorgio P, Della Mura B, Moliterni S, Spagnoletta A, Dimatteo S, et al. Tenebrio molitor Frass: A Cutting-Edge Biofertilizer for Sustainable Agriculture and Advanced Adsorbent Precursor for Environmental Remediation. Agronomy. 2025 Mar 20;15(3):758. doi:10.3390/agronomy15030758
39. Truzzi C, Illuminati S, Girolametti F, Antonucci M, Scarponi G, Ruschioni S, et al. Influence of Feeding Substrates on the Presence of Toxic Metals (Cd, Pb, Ni, As, Hg) in Larvae of Tenebrio molitor: Risk Assessment for Human Consumption. Int J Environ Res Public Health. 2019 Nov 30;16(23):4815. doi:10.3390/ijerph16234815
40. Debache K. Growth performance of novel food based on mixture of boiled-dried granulated Tenebrio molitor larvae and date-fruit waste in broiler chicken farming. Asian J Agric. 2021 Feb 2;5(1). doi:10.13057/asianjagric/g050104
41. Aguilar-Toalá JE, Vidal-Limón AM, Liceaga AM. Advancing Food Security with Farmed Edible Insects: Economic, Social, and Environmental Aspects. Insects. 2025 Jan 11;16(1):67. doi:10.3390/insects16010067
42. Pöllinger-Zierler B, Lienhard A, Mayer C, Berner S, Rehorska R, Schöpfer A, et al. Tenebrio molitor (Linnaeus, 1758): Microbiological Screening of Feed for a Safe Food Choice. Foods. 2023 May 25;12(11):2139. doi:10.3390/foods12112139
43. Dalmoro YK, Franceschi CH, Stefanello C. A Systematic Review and Metanalysis on the Use of Hermetia illucens and Tenebrio molitor in Diets for Poultry. Vet Sci. 2023 Dec 12;10(12):702. doi:10.3390/vetsci10120702
44. Kotsou K, Chatzimitakos T, Athanasiadis V, Bozinou E, Lalas SI. Exploiting Agri-Food Waste as Feed for Tenebrio molitor Larvae Rearing: A Review. Foods. 2024 Mar 27;13(7):1027. doi:10.3390/foods13071027
45. Verni M, Squeo G, Perri G, Demarinis C, Rizzello CG, Caponio F, et al. Optimizing Tenebrio molitor powder as ingredient in breadmaking: Impact of enzymatic hydrolysis on dough techno-functional properties and bread quality. Future Foods. 2025 Jun;11:100665. doi:10.1016/j.fufo.2025.100665
46. Kröncke N, Wittke S, Steinmann N, Benning R. Analysis of the Composition of Different Instars of Tenebrio molitor Larvae using Near-Infrared Reflectance Spectroscopy for Prediction of Amino and Fatty Acid Content. Insects. 2023 Mar 23;14(4):310. doi:10.3390/insects14040310
47. Nieto J, Plaza J, Lara J, Abecia JA, Revilla I, Palacios C. Performance of Slow-Growing Chickens Fed with Tenebrio molitor Larval Meal as a Full Replacement for Soybean Meal. Vet Sci. 2022 Mar 12;9(3):131. doi:10.3390/vetsci9030131
48. Vasilopoulos S, Giannenas I, Savvidou S, Bonos E, Rumbos CI, Papadopoulos E, et al. Growth performance, welfare traits and meat characteristics of broilers fed diets partly replaced with whole Tenebrio molitor larvae. Anim Nutr. 2023 Jun;13:90–100. doi:10.1016/j.aninu.2022.12.002
49. López-Gámez G, Del Pino-García R, López-Bascón MA, Verardo V. Improving Tenebrio molitor Growth and Nutritional Value through Vegetable Waste Supplementation. Foods. 2024 Feb 16;13(4):594. doi:10.3390/foods13040594
50. Petkov E, Popova T, Dimov K, Vlahova-Vangelova D, Balev D, Kolev N, et al. Low-Fat Tenebrio molitor Meal as a Component in the Broiler Diet: Growth Performance and Carcass Composition. Insects. 2024 Dec 11;15(12):979. doi:10.3390/insects15120979

51. Biasato I, Gariglio M, Bongiorno V, Fiorilla E, Cappone EE, Bellezza Oddon S, et al. Can a mixture of Hermetia illucens and Tenebrio molitor meals be feasible to feed broiler chickens? A focus on bird productive performance, nutrient digestibility, and meat quality. Poult Sci. 2025 Jul;104(7):105150. doi:10.1016/j.psj.2025.105150
52. Secci G, Dabbou S, Lira de Medeiros AC, Addeo NF, Atallah E, Parisi G, et al. Low dietary inclusion levels of Tenebrio molitor larva meal slightly modify growth performance, carcass and meat traits of Japanese quail (Coturnix japonica). J Sci Food Agric. 2022 Nov;102(14):6578–85. doi:10.1002/jsfa.12023 PubMed PMID: 35596626.
53. Hammer L, Moretti D, Abbühl-Eng L, Kandiah P, Hilaj N, Portmann R, et al. Mealworm larvae (Tenebrio molitor) and crickets (Acheta domesticus) show high total protein in vitro digestibility and can provide good-to-excellent protein quality as determined by in vitro DIAAS. Front Nutr. 2023 Jul 3;10:1150581. doi:10.3389/fnut.2023.1150581
54. Meyer S, Gessner DK, Braune MS, Friedhoff T, Most E, Höring M, et al. Comprehensive evaluation of the metabolic effects of insect meal from Tenebrio molitor L. in growing pigs by transcriptomics, metabolomics and lipidomics. J Anim Sci Biotechnol. 2020;11:20. doi:10.1186/s40104-020-0425-7 PubMed PMID: 32158542; PubMed Central PMCID: PMC7055059.
55. Zacharis C, Bonos E, Giannenas I, Skoufos I, Tzora A, Voidarou C (Chrysa), et al. Utilization of Tenebrio molitor Larvae Reared with Different Substrates as Feed Ingredients in Growing Pigs. Vet Sci. 2023 Jun 9;10(6):393. doi:10.3390/vetsci10060393
56. Chemello G, Renna M, Caimi C, Guerreiro I, Oliva-Teles A, Enes P, et al. Partially Defatted Tenebrio molitor Larva Meal in Diets for Grow-Out Rainbow Trout, Oncorhynchus mykiss (Walbaum): Effects on Growth Performance, Diet Digestibility and Metabolic Responses. Animals. 2020 Jan 31;10(2):229. doi:10.3390/ani10020229
57. Gonzalez-de La Rosa T, Montserrat-de La Paz S, Rivero-Pino F. Production, characterisation, and biological properties of Tenebrio molitor-derived oligopeptides. Food Chem. 2024 Aug;450:139400. doi:10.1016/j.foodchem.2024.139400
58. Villanova JCV, Pretto A, Penchel EM, Serra SDS, Lanes CFC, Ribeiro VB, et al. Bioactive peptides from Tenebrio molitor: physicochemical and antioxidant properties and antimicrobial capacity. An Acad Bras Cienc. 2024;96(suppl 1):e20231375. doi:10.1590/0001-3765202320231375 PubMed PMID: 39319835.
59. Ma W, Yang J, Suo H, Song J. Tenebrio molitor proteins and peptides: Cutting-edge insights into bioactivity and expanded food applications. Food Biosci. 2025 Jun;68:106369. doi:10.1016/j.fbio.2025.106369
60. Stephan MP, Sarkis JEDS, Rosa JSD, Cocato ML. Tenebrio Molitor: Investigating the Scientific Foundations and Proteomic and Peptidomic Potential. Food Nutr Sci. 2025;16(04):427–35. doi:10.4236/fns.2025.164024
61. Du Z, Wang D, Li Y. Comprehensive Evaluation and Comparison of Machine Learning Methods in QSAR Modeling of Antioxidant Tripeptides. ACS Omega. 2022 Jul 26;7(29):25760–71. doi:10.1021/acsomega.2c03062 PubMed PMID: 35910147; PubMed Central PMCID: PMC9330208.
62. Rivero Pino F, Pérez Gálvez R, Espejo Carpio FJ, Guadix EM. Evaluation of Tenebrio molitor protein as a source of peptides for modulating physiological processes. Food Funct. 2020 May 1;11(5):4376–86. doi:10.1039/d0fo00734j PubMed PMID: 32373903.
63. Ferrazzano GF, D'Ambrosio F, Caruso S, Gatto R, Caruso S. Bioactive Peptides Derived from Edible Insects: Effects on Human Health and Possible Applications in Dentistry. Nutrients. 2023 Oct 30;15(21):4611. doi:10.3390/nu15214611
64. Tan J, Yang J, Zhou X, Hamdy AM, Zhang X, Suo H, et al. Tenebrio molitor Proteins-Derived DPP-4 Inhibitory Peptides: Preparation, Identification, and Molecular Binding Mechanism. Foods. 2022 Nov 13;11(22):3626. doi:10.3390/foods11223626
65. Brai A, Immacolata Trivisani C, Vagaggini C, Stella R, Angeletti R, Iovenitti G, et al. Proteins from Tenebrio molitor: An interesting functional ingredient and a source of ACE inhibitory peptides. Food Chem. 2022 Nov;393:133409. doi:10.1016/j.foodchem.2022.133409
66. Berraquero-García C, Martínez-Sánchez L, Guadix EM, García-Moreno PJ. Encapsulation of Tenebrio molitor Hydrolysate with DPP-IV Inhibitory Activity by Electrospraying and Spray-Drying. Nanomaterials. 2024 May 10;14(10):840. doi:10.3390/nano14100840

67. Deacon CF, Wamberg S, Bie P, Hughes TE, Holst JJ. Preservation of active incretin hormones by inhibition of dipeptidyl peptidase IV suppresses meal-induced incretin secretion in dogs. J Endocrinol. 2002 Feb;172(2):355–62. doi:10.1677/joe.0.1720355 PubMed PMID: 11834453.
68. Pessina F, Frosini M, Marcolongo P, Fusi F, Saponara S, Gamberucci A, et al. Antihypertensive, cardio- and neuro-protective effects of Tenebrio molitor (Coleoptera: Tenebrionidae) defatted larvae in spontaneously hypertensive rats. Quintas LEM, editor. PLOS ONE. 2020 May 29;15(5):e0233788. doi:10.1371/journal.pone.0233788
69. Tran NB, Lee H, Ji MG, Ngo Hoang L, Lee SJ. The synergistic extract of Zophobas atratus and Tenebrio molitor regulates neuroplasticity and oxidative stress in a scopolamine-induced cognitive impairment model. Front Aging Neurosci. 2025 Apr 23;17. doi:10.3389/fnagi.2025.1566621
70. Fan M, Wedamulla NE, Choi YJ, Zhang Q, Bae SM, Kim EK. Tenebrio molitor Larva Trypsin Hydrolysate Ameliorates Atopic Dermatitis in C57BL/6 Mice by Targeting the TLR-Mediated MyD88-Dependent MAPK Signaling Pathway. Nutrients. 2022 Dec 24;15(1):93. doi:10.3390/nu15010093
71. Verheyen GR, Meersman F, Noyens I, Goossens S, Van Miert S. The Application of Mealworm (*Tenebrio molitor*) Oil in Cosmetic Formulations. Eur J Lipid Sci Technol. 2023 Mar;125(3). doi:10.1002/ejlt.202200193
72. Ngoc LTN, Moon JY, Lee YC. Insights into Bioactive Peptides in Cosmetics. Cosmetics. 2023 Aug 2;10(4):111. doi:10.3390/cosmetics10040111
73. Gonzalez-de La Rosa T, Marquez-Paradas E, Leon MJ, Montserrat-de La Paz S, Rivero-Pino F. Exploring Tenebrio molitor as a source of low-molecular-weight antimicrobial peptides using a n in silico approach: correlation of molecular features and molecular docking. J Sci Food Agric. 2025 Feb;105(3):1711–36. doi:10.1002/jsfa.13949
74. Jo HS, Song DB, Lee SH, Lee KS, Yang J, Hong SM. Concurrent Hydrolysis–Fermentation of Tenebrio molitor Protein by Lactobacillus plantarum KCCM13068P Attenuates Inflammation in RAW 264.7 Macrophages and Constipation in Loperamide-Induced Mice. Foods. 2025 May 26;14(11):1886. doi:10.3390/foods14111886
75. Torres-Acosta RI, Moreno-Ramírez YDR, García-García LD, Espinoza-Sánchez EA, Juárez-Aragón MC, De Los Santos RT, et al. Insects with Phenolics and Antioxidant Activities to Supplement Mezcal: Tenebrio molitor L.1 and Schistocerca piceifrons Walker2. Southwest Entomol. 2021 Sep 29;46(3). doi:10.3958/059.046.0304
76. Vrontaki M, Adamaki-Sotiraki C, Rumbos CI, Anastasiadis A, Athanassiou CG. Valorization of local agricultural by-products as nutritional substrates for Tenebrio molitor larvae: A sustainable approach to alternative protein production. Environ Sci Pollut Res. 2024 May 14;31(24):35760–8. doi:10.1007/s11356-024-33564-8
77. Fondevila G, Remiro A, Fondevila M. Growth performance and chemical composition of Tenebrio molitor larvae grown on substrates with different starch to fibre ratios. Ital J Anim Sci. 2024 Dec 31;23(1):887–94. doi:10.1080/1828051x.2024.2362765
78. Yakti W, Schulz S, Förster N, Deruytter D, Müller M, Mewis I, et al. Utilising common bean and strawberry vegetative wastes in yellow mealworm (Tenebrio molitor) substrates: effects of pre-treatment on growth and composition. Sci Rep. 2025 Mar 5;15(1). doi:10.1038/s41598-025-91732-3
79. Lopes IG, Gómez-Brandón M, Praeg N, Claeys J, Yakti W, Bitterlich M, et al. BugBook: Critical considerations for evaluating and applying insect frass. J Insects Food Feed. 2025 Jun 25;1–28. doi:10.1163/23524588-bja10254
80. Muñoz-Seijas N, Fernandes H, Outeiriño D, Morán-Aguilar MG, Domínguez JM, Salgado JM. Potential use of frass from edible insect Tenebrio molitor for proteases production by solid-state fermentation. Food Bioprod Process. 2024 Mar;144:146–55. doi:10.1016/j.fbp.2024.01.002
81. Magro AD, Lovarelli D, Bacenetti J, Guarino M. The potential of insect frass for sustainable biogas and biomethane production: A review. Bioresour Technol. 2024 Nov;412:131384. doi:10.1016/j.biortech.2024.131384
82. He L, Yang SS, Bai SW, Pang JW, Liu GS, Cao GL, et al. Fabrication and environmental assessment of photo-assisted Fenton-like Fe/FBC catalyst utilizing mealworm frass waste. J Clean Prod. 2020 May;256:120259. doi:10.1016/j.jclepro.2020.120259

83. Muñoz-Seijas N, Fernandes H, Domínguez JM, Salgado JM. Recent Advances in Biorefinery of Tenebrio molitor Adopting Green Technologies. Food Bioprocess Technol. 2025 Feb;18(2):1061–78. doi:10.1007/s11947-024-03510-0
84. Moruzzo R, Riccioli F, Espinosa Diaz S, Secci C, Poli G, Mancini S. Mealworm (Tenebrio molitor): Potential and Challenges to Promote Circular Economy. Animals. 2021 Aug 31;11(9):2568. doi:10.3390/ani11092568
85. Maria Vodenicharova. Supply Chain Challenges of Insect Protein. Nanotechnol Percept [Internet]. 2024;20(S11 (Special Issue)):1570–82. Available from: https://www.nano-ntp.com
86. Azzi M, Elkadaoui S, Zim J, Desbrieres J, El Hachimi Y, Tolaimate A. Tenebrio Molitor breeding rejects as a high source of pure chitin and chitosan: Role of the processes, influence of the life cycle stages and comparison with Hermetia illucens. Int J Biol Macromol. 2024 Oct;277:134475. doi:10.1016/j.ijbiomac.2024.134475
87. Izadi H, Asadi H, Bemani M. Chitin: a comparison between its main sources. Front Mater. 2025 Mar 4;12. doi:10.3389/fmats.2025.1537067
88. Terkula Iber B, Azman Kasan N, Torsabo D, Wese Omuwa J. A Review of Various Sources of Chitin and Chitosan in Nature. J Renew Mater. 2022;10(4):1097–123. doi:10.32604/jrm.2022.018142
89. Nafary A, Mousavi Nezhad SA, Jalili S. Extraction and Characterization of Chitin and Chitosan from Tenebrio Molitor Beetles and Investigation of Its Antibacterial Effect Against Pseudomonas aeruginosa. Adv Biomed Res. 2023 Apr;12(1). doi:10.4103/abr.abr_205_22
90. Perez JT, Casanova F, Queiroz LS, Petersen HO, García-Moreno PJ, Feyissa AH. Protein extraction from yellow mealworm (Tenebrio molitor) assisted by pulsed electric fields: Effect on foaming properties. LWT. 2024 Dec;213:117041. doi:10.1016/j.lwt.2024.117041
91. Martínez-Pineda M, Juan T, Antoniewska-Krzeska A, Vercet A, Abenoza M, Yagüe-Ruiz C, et al. Exploring the Potential of Yellow Mealworm (Tenebrio molitor) Oil as a Nutraceutical Ingredient. Foods. 2024 Nov 29;13(23):3867. doi:10.3390/foods13233867
92. Jeong S, Oh I. Characterization of mixed-component oleogels: Beeswax and glycerol monostearate interactions towards Tenebrio Molitor larvae oil. Curr Res Food Sci. 2024;8:100689. doi:10.1016/j.crfs.2024.100689
93. Kim D, Oh I. The Characteristic of Insect Oil for a Potential Component of Oleogel and Its Application as a Solid Fat Replacer in Cookies. Gels. 2022 Jun 6;8(6):355. doi:10.3390/gels8060355
94. Brai A, Neri C, Tarchi F, Poggialini F, Vagaggini C, Frosinini R, et al. Upcycling Milk Industry Byproducts into Tenebrio molitor Larvae: Investigation on Fat, Protein, and Sugar Composition. Foods. 2024 Oct 29;13(21):3450. doi:10.3390/foods13213450
95. Mamtimin T, Han H, Khan A, Feng P, Zhang Q, Ma X, et al. Gut microbiome of mealworms (Tenebrio molitor Larvae) show similar responses to polystyrene and corn straw diets. Microbiome. 2023 May 5;11(1). doi:10.1186/s40168-023-01550-w
96. Wang X, Du R, Henriquez FN, Liu H, Chan SY, Leong CM, et al. Enhancing Plastic Decomposition in Mealworms (*Tenebrio molitor*): The Role of Nutritional Amino Acids and Water. Adv Energy Sustain Res. 2025 Jun;6(6). doi:10.1002/aesr.202400378
97. Mamtimin T, Ouyang X, Wu WM, Zhou T, Hou X, Khan A, et al. Novel Feruloyl Esterase for the Degradation of Polyethylene Terephthalate (PET) Screened from the Gut Microbiome of Plastic-Degrading Mealworms (*Tenebrio Molitor* Larvae). Environ Sci Technol. 2024 Oct 8;58(40):17717–31. doi:10.1021/acs.est.4c01495
98. Dávalos Terán I, Imai K, Lacroix IME, Fogliano V, Udenigwe CC. Bioinformatics of edible yellow mealworm (*Tenebrio molitor*) proteome reveal the cuticular proteins as promising precursors of dipeptidyl peptidase-IV inhibitors. J Food Biochem. 2020 Feb;44(2). doi:10.1111/jfbc.13121
99. Janković-Tomanić M, Petković B, Vranković JS, Perić-Mataruga V. Effects of high doses of zearalenone on some antioxidant enzymes and locomotion of *Tenebrio molitor* larvae (Coleoptera: Tenebrionidae). Athanassiou C, editor. J Insect Sci. 2024 May 1;24(3). doi:10.1093/jisesa/ieae052
100. Chamani M, Dadpour M, Dehghanian Z, Panahirad S, Chenari Bouket A, Oszako T, et al. From Digestion to Detoxification: Exploring Plant Metabolite Impacts on Insect Enzyme Systems for Enhanced Pest Control. Insects. 2025 Apr 7;16(4):392. doi:10.3390/insects16040392

101. Winkiel MJ, Chowański S, Walkowiak-Nowicka K, Gołębiowski M, Słocińska M. A tomato a day keeps the beetle away – the impact of Solanaceae glycoalkaloids on energy management in the mealworm Tenebrio molitor. Environ Sci Pollut Res. 2024 Sep 25;31(48):58581–98. doi:10.1007/s11356-024-35099-4
102. Winkiel MJ, Chowański S, Gołębiowski M, Bufo SA, Słocińska M. Solanaceae Glycoalkaloids Disturb Lipid Metabolism in the Tenebrio molitor Beetle. Metabolites. 2023 Nov 30;13(12):1179. doi:10.3390/metabo13121179
103. Walkowiak-Nowicka K, Mirek J, Chowański S, Sobkowiak R, Słocińska M. Plant secondary metabolites as potential bioinsecticides? Study of the effects of plant-derived volatile organic compounds on the reproduction and behaviour of the pest beetle Tenebrio molitor. Ecotoxicol Environ Saf. 2023 Jun;257:114951. doi:10.1016/j.ecoenv.2023.114951
104. Jiang T, Zhao X, Li H, Zhang L, Tang B, Ding Y, et al. Effects of yellow mealworm (Tenebrio molitor) larvae meal on the growth performance, serum biochemical parameters and caecal metabolome in broiler chickens. Ital J Anim Sci. 2024 Dec 31;23(1):813–23. doi:10.1080/1828051x.2024.2350230
105. Benashvili M, Lee S, Ju YW, Park YJ, Kim SA, Park SW, et al. Effect of mealworm (Tenebrio molitor L.) chitosan coating on the postharvest qualities of strawberries. Postharvest Biol Technol. 2025 Oct;228:113657. doi:10.1016/j.postharvbio.2025.113657
106. Liu M, Zou X, Wu X, Li X, Chen H, Pan F, et al. Preparation of chitosan/Tenebrio molitor larvae protein/curcumin active packaging film and its application in blueberry preservation. Int J Biol Macromol. 2024 Aug;275:133675. doi:10.1016/j.ijbiomac.2024.133675
107. Mwita CS, Muhammad R, Nettey-Oppong EE, Enkhbayar D, Ali A, Ahn J, et al. Chitosan Extracted from the Biomass of Tenebrio molitor Larvae as a Sustainable Packaging Film. Materials. 2024 Jul 25;17(15):3670. doi:10.3390/ma17153670
108. Ilijin L, Popović D, Živković M, Todorović D, Mrdaković M, Vlahović M, et al. The impact of co-fed plastic diet on Tenebrio molitor gut bacterial community structure. Sci Rep. 2025 Jul 1;15(1). doi:10.1038/s41598-025-04805-8
109. Wang X, Tang T. Effects of Polystyrene Diet on the Growth and Development of Tenebrio molitor. Toxics. 2022 Oct 13;10(10):608. doi:10.3390/toxics10100608
110. Mersmann L, Souza VGL, Fernando AL. Green Processes for Chitin and Chitosan Production from Insects: Current State, Challenges, and Opportunities. Polymers. 2025 Apr 26;17(9):1185. doi:10.3390/polym17091185
111. Morganti P, Morganti G, Coltelli MB. Natural Polymers and Cosmeceuticals for a Healthy and Circular Life: The Examples of Chitin, Chitosan, and Lignin. Cosmetics. 2023 Feb 28;10(2):42. doi:10.3390/cosmetics10020042
112. Yin H, Zhang S, Yue H, Wang M, Zeng J, Wu W, et al. Isolation, identification and in silico analysis of two novel cytoprotective peptides from tilapia skin against oxidative stress-induced ovarian granulosa cell damage. J Funct Foods. 2023 Aug;107:105629. doi:10.1016/j.jff.2023.105629
113. Leipertz M, Hogeveen H, Saatkamp HW. Economic supply chain modelling of industrial insect production in the Netherlands. J Insects Food Feed. 2024 Mar 15;10(8):1361–85. doi:10.1163/23524588-00001036
114. Modahl IS, Brekke A. Environmental performance of insect protein: a case of LCA results for fish feed produced in Norway. SN Appl Sci. 2022 Jun;4(6). doi:10.1007/s42452-022-05065-1
115. Vinci G, Prencipe SA, Masiello L, Zaki MG. The Application of Life Cycle Assessment to Evaluate the Environmental Impacts of Edible Insects as a Protein Source. Earth. 2022 Aug 20;3(3):925–38. doi:10.3390/earth3030054
116. Villaró-Cos S, Guzmán Sánchez JL, Acién G, Lafarga T. Research trends and current requirements and challenges in the industrial production of spirulina as a food source. Trends Food Sci Technol. 2024 Jan;143:104280. doi:10.1016/j.tifs.2023.104280
117. Morena F, Cencini C, Calzoni E, Martino S, Emiliani C. A Novel Workflow for In Silico Prediction of Bioactive Peptides: An Exploration of Solanum lycopersicum By-Products. Biomolecules. 2024 Jul 31;14(8):930. doi:10.3390/biom14080930

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 16 April 2026 doi:10.20944/preprints202509.0944.v5

118. Meijer N, Safitri RA, Tao W, Hoek-Van Den Hil EF. Review: European Union legislation and regulatory framework for edible insect production – Safety issues. animal. 2025 Feb;101468. doi:10.1016/j.animal.2025.101468
119. Verardi A, Sangiorgio P, Della Mura B, Moliterni S, Spagnoletta A, Dimatteo S, et al. Tenebrio molitor Frass: A Cutting-Edge Biofertilizer for Sustainable Agriculture and Advanced Adsorbent Precursor for Environmental Remediation. Agronomy. 2025 Mar 20;15(3):758. doi:10.3390/agronomy15030758