

Review

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

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Review

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

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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 CO₂-eq, 213.7 MJ of non-renewable energy use, and 22.4 m² 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 current regulatory landscape surrounding *T. molitor*, including authorization processes, safety assessments, and allergenicity evaluations critical for its integration into food and feed systems. Rather than an extended background, this section defines the regulatory and safety constraints that condition deployment and scaling of *T. molitor* across production contexts, including decentralized low-input systems relevant to arid regions. These constraints are referenced later when discussing sustainability bottlenecks and scale-up.

2.1. Regulatory Landscape and Approvals

Since 2021, the European Union has approved the use of processed insect proteins (PIPs) in poultry and pig feed, marking an important step in the integration of insects into the agri-food chain [19]. In parallel, the EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA) concluded that frozen and dried whole *T. molitor* larvae are safe for human consumption as a Novel Food, under defined specifications and labelling requirements, and this conclusion has been reaffirmed in subsequent EFSA opinions [15,20]. Regulatory initiatives are also advancing outside Europe. In Asia, South Korea, through its Ministry of Agriculture (MAFRA), is promoting sustainable approaches that integrate insects into national agricultural policies. Regional consultations supported by FAO Korea Partnership (2022) have fostered South-South cooperation. These initiatives are now shaping harmonized regulations across Asia and Africa. They are also paving the way for the transnational recognition of *T. molitor* as a food and functional ingredient [21].

In January 2025, the European Commission extended this recognition by authorizing the commercialization of whole *T. molitor* powder treated with UV irradiation. This decision (Implementing Regulation (EU) 2025/89) facilitates its incorporation into processed foods such as breakfast cereals, dairy products, and snacks [22]. Meanwhile, in Switzerland, the sale of *T. molitor* for human consumption has been legal since 2017.

From a microbiological perspective, EFSA reports that post-harvest processing includes a 24 h fasting step and a blanching step, which contributes to reducing the microbial load and to the elimination of potentially present viruses or parasites [20]. Regulation (EU) 2015/2283 provides the legal basis for Novel Food authorisation. Before EU-wide authorisations, whole insects were already marketed in several EU Member States under national approaches. Regulation (EU) 2015/2283 includes transitional measures in Article 35(2), allowing continued marketing for certain foods lawfully placed on the market on 1 January 2018 while an authorisation decision is pending [23]. However, differences in labelling practices and market access requirements can still slow commercialization [24].

2.2. Safety, Toxicology, and Allergenicity

Malematja et al. studied how heavy metals accumulate in feeder insects. Their work included cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), copper (Cu), and zinc (Zn). *T. molitor*, raised on substrates with controlled contamination, showed measurable uptake of Cd and Pb. The authors noted that “substrate composition directly shaped accumulation levels,” suggesting diet is a key driver [25]. These data provide baseline values but also highlight knowledge gaps, including stage-specific differences and the need for matrix-specific regulatory benchmarks. At EU level, maximum levels for contaminants are defined by the European Commission and depend on the relevant food matrix. For edible insects, dedicated benchmarks remain limited, which complicates direct compliance comparisons and underscores the need for harmonised reference values. Machona and collaborators tested powdered *T. molitor* larvae in Sprague-Dawley rats for 70 days at 300, 1000, and 3000 mg/kg/day. They reported no deaths or clinical signs of toxicity. Body weight, food intake, and organ weight ratios stayed within normal ranges. A small change in liver weight appeared, though it was not statistically significant. “No adverse effects were observed under the tested conditions”, the authors concluded. However, the study’s limited duration and the absence of genotoxicity and reproductive endpoints indicate that longer-term datasets are still needed to strengthen the overall safety assessment [26]. EFSA concluded that frozen and dried whole *T. molitor* larvae can be used as a novel food under specific conditions. Allergenicity must be controlled and labelling must be clear. The assessment covered composition, processing, stability, and microbiological criteria [15].

Öllinger-Zierler and colleagues further reported that properly processed batches maintain consistent microbiological quality under Hazard Analysis and Critical Control Points (HACCP) monitoring, with total viable counts 3.5–4.2 log CFU/g, no detectable *Salmonella* or *Listeria*, *Bacillus cereus* spores <10² CFU/g, fungal loads around 2.3 log CFU/g (mainly *Aspergillus* and *Penicillium*), and no harmful levels of mycotoxins [27]. This was consistent with the sub-chronic toxicity findings reported above [26]. Nevertheless, EFSA acknowledged the absence of post-market epidemiological data, which is a common gap for novel foods. Allergenicity remains a central issue. Majsiak and collaborators examined sensitization to *T. molitor* in allergic patients with different sensitization profiles. They used the multiplex Allergy Explorer 2 (ALEX2) assay. They cautioned that the presence of specific immunoglobulin E (sIgE) does not equal clinical allergy [28]. In a separate real life prevalence study in insect food naive allergic individuals, Scala and collaborators used ALEX2 to assess immunoglobulin E (IgE) reactivity to cricket, locust, and mealworm. They reported component level IgE reactivity, including tropomyosin and arginine kinase [29]. However, sensitization does not necessarily predict clinical reactions. Cross-reactivity with crustaceans and mites supports European Union (EU) mandatory labelling. Oral food challenges remain limited, but clinical reactions to insect ingestion have been documented [28,30]. Reports of severe reactions, including anaphylaxis observed in some Asian cohorts, further support the need for careful monitoring as *T. molitor* enters human

diets. Taken together, these safety and allergenicity considerations are not specific to one production model, but they shape monitoring needs and compliance capacity, which can become limiting factors in both industrial scaling and decentralized low-input settings.

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 (P₂O₅) from 1.5 % to 2.4 %, and potassium (K₂O) 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 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 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 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]. In a separate, unpublished trial conducted in Biskra, Algeria, larvae from the same batch were reared either on downgraded local dates, a readily available by-product in the region, or on assorted vegetable scraps. These observations are unpublished and included only as an illustrative example; they should be interpreted as a knowledge gap requiring validation. Both groups completed their development over the same period with no adverse effects observed, and growth rates were comparable, even without measuring protein or lipid contents. Notably, this dual advantage, lower costs and maintained performance, illustrates the potential of waste stream utilization as a driver of sustainable value chains.

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 [40].

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 [41]. 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 [41–43]. 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 [43]. 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 [43]. 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 [5,42]. The larvae further provide notable amounts of oleic acid (27-32%) and a saturated fraction (21-26%) dominated by palmitic acid at roughly 15% [43]. 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 [41]. 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. What's particularly clever is how food technologists are overcoming potential sensory challenges, through fine milling, careful flavor masking, and strategic 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 [44]. 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 [45]. For producers, this is more than a detail. It means harvest timing can be adapted in practice, either to secure the highest possible protein yield, or to target a specific fatty acid profile depending on the product's intended use. 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 [46,47]. Studies using inclusion levels as low as 5-10 % have still shown measurable gains in growth and feed efficiency [47–49]. 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 [46]. 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 [50]. 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 [51]. 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 [52]. 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 [53]. 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 [54].

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 [55]. We then move from feed performance to bioactive compounds and functional ingredients.

6. Bioactive Compounds and Human Health Applications

The nutritional quality of *T. molitor* has been increasingly linked to its bioactive peptide fraction. Recent work identified cryptides (2-20 amino acids) generated by controlled enzymatic hydrolysis of *T. molitor* proteins and further released during simulated human gastrointestinal digestion. Antioxidant capacity was confirmed via DPPH radical-scavenging ($EC_{50} \approx 0.30-0.87$ mg/mL). In LPS-stimulated human Caco-2 cells, digestion-derived hydrolysates down-regulated pro-inflammatory genes (TNF- α , IFN- γ , IL-6; modest effect on IL-1 β) and up-regulated IL-4, with *in silico* docking suggesting interaction with the TLR4/MD2 complex [56]. On this basis, Hammer and collaborators further investigated the protein quality of *T. molitor*, using *in vitro* digestibility and DIAAS as indicators. The study also compared results with *Acheta domesticus* as a reference species. Interestingly, cricket proteins also showed digestibility above 90% [52]. For *T. molitor*, Khanal and collaborators confirmed similarly high digestibility and DIAAS values, consistent with the data already presented in Section 4 [3]. Overall, the evidence base remains preclinical. *In vitro* assays provide consistent signals but typically at mg/mL concentrations. Animal studies offer limited *in vivo* support, often short-term. Translation to human health therefore remains preliminary and requires pharmacokinetics and controlled clinical studies.

Recent syntheses reinforce this evidence base: comprehensive reviews describe multiple families of *T. molitor*-derived peptides (antioxidant, anti-inflammatory, antihypertensive, immunomodulatory) and consolidate analytical workflows (HPLC-MS/MS, targeted bioassays) supporting their health relevance [57,58]. In parallel to enzymatic routes, gentle non-thermal processing can also help. Perez and colleagues applied pulsed electric fields to defatted *T. molitor* and increased protein extraction yield while improving foaming capacity and foam stability. The treatment subtly altered protein structure, which likely explains the better techno-functionality for health-oriented formulations [59]. Evidence from process-standardized hydrolysates further supports these findings. An Alcalase-based protocol produced peptide fractions with both antioxidant activity and antimicrobial action, effective against *Staphylococcus aureus* and *Escherichia coli* [60]. Time-resolved hydrolysis experiments showed a progressive rise in free amino groups and a parallel increase in radical-scavenging capacity. These results support the antioxidant profile of *T. molitor* protein hydrolysates under optimized reaction windows [5]. Ferrazzano and collaborators reviewed the short tripeptide YAN (tyrosine-alanine-asparagine) in a rat model of hypertension. The animals were treated and a fall in blood pressure was observed. Signs of endothelial improvement were also noted, and the effect was linked to inhibition of the angiotensin-converting enzyme (ACE) [61].

In parallel, Kotsou and collaborators reviewed peptide fractions obtained from *T. molitor* hydrolysates and summarized *in vitro* ACE-inhibitory activity ($IC_{50} \approx 0.25$ mg/mL) [18]. Consistent with these reports, an experimental study on *T. molitor* hydrolysates produced with food-grade proteases measured DPPH radical-scavenging and ferric-reducing activities [62]. Structure-activity modelling of antioxidant tripeptides indicates that residue composition can influence scavenging potency [63]. Extending this cardiometabolic perspective, Tan and collaborators (2022) identified *T. molitor*-derived peptides with strong affinity for dipeptidyl peptidase-IV (DPP-IV), a key regulator of postprandial glucose homeostasis. Their inhibitory capacity ($IC_{50} \approx 1.64$ mg/mL) suggests potential for modulating glucose metabolism, an effect of interest for type 2 diabetes prevention [64]. These experimental findings are consistent with an earlier *in silico* pipeline that mined 384 *T. molitor* proteins and prioritized cuticular proteins as precursors of potent DPP-IV inhibitory peptides, thereby guiding targeted hydrolysis and validation strategies [65].

Computational pipelines can support peptide discovery and prioritisation from *T. molitor* hydrolysates, but candidate activity still requires experimental validation [66]. Similar *in silico* and modelling workflows were first developed on non-insect proteins and can be adapted to insect matrices [67,68]. Brai and collaborators reported ACE-inhibitory peptides from *T. molitor*, targeting the angiotensin-converting enzyme (ACE), a key regulator of blood pressure and an established target in hypertension therapy [69]. YAN had also been reported earlier in this section in an

independent preclinical context, supporting its relevance as a recurring ACE-inhibitory motif [61]. Overall, these findings extend the pool of cardiovascular-relevant candidates but remain within a preclinical evidence tier.

In line with these cardiovascular observations, Pessina and co-authors (2020) carried out an *in vivo* experiment on spontaneously hypertensive rats, a common model in human hypertension research. After oral intake of defatted *T. molitor* larval extracts, the animals’ systolic blood pressure dropped. Heart function also improved, with a noticeable rise in ejection fraction and fractional shortening. Interestingly, this was not the only change. The same treatment coincided with higher levels of brain-derived neurotrophic factor (BDNF) and a drop in lipid peroxidation. The authors also observed signs of reduced oxidative stress, along with lower amounts of pro-inflammatory cytokines such as TNF- α and IL-1 β [70].

Still within the scope of human health, the incretin hormones GLP-1 and GIP regulate postprandial insulin release but are degraded by the enzyme DPP-4. This enzyme shortens incretin action, reducing their effect on glucose regulation [71]. Berraquero-García and collaborators (2024) examined *T. molitor* peptides for their ability to inhibit DPP-4 ($IC_{50} \approx 1.7$ mg/mL). The material was processed through electrospraying and spray-drying to preserve this activity and enable nutraceutical formulation. Both encapsulation methods maintained the inhibitory effect, making them relevant for dietary strategies supporting metabolic function [72]. Complementarily, fermenting *T. molitor* hydrolysates with *Lactobacillus plantarum* enhanced anti-inflammatory readouts in macrophages and improved gastrointestinal motility in a murine constipation model, suggesting microbiome-coupled routes to increase physiological relevance [73].

Turning to cognitive aspects of human health, recent research has explored potential brain-related benefits. Tran and collaborators tested a mixed extract from *Zophobas atratus* and *T. molitor* in mice model with scopolamine-induced memory impairment. Behavioural assessments, including the Morris water maze and Y-maze, showed marked gains in memory. In this model, the gains were accompanied by modulation of AMPK/SIRT1 and BDNF-Akt/mTOR pathways, which are key for synaptic plasticity, oxidative stress control, and neuronal repair [74]. LC-MS/MS analysis then pointed to two main groups of compounds: glycosides (31 %) and heterocycles (27 %). Both classes are known from other contexts to exert neuroprotective effects, particularly under inflammation or during aging [74]. Methanolic extracts of *T. molitor* containing phenolics also showed measurable antioxidant activity in DPPH and FRAP assays [75]. This highlights that, beyond peptides, insect-derived metabolites may also contribute to nutritional interest. Dermatological/dermocosmetic lines of evidence are also accumulating: a recent review synthesizes peptide-based anti-ageing, moisturizing and soothing mechanisms relevant to skin care [76]; *in vivo*, trypsin hydrolysates alleviated atopic dermatitis signs via TLR-MyD88-MAPK modulation [77]; and *T. molitor* oil showed moisturizing and cytoprotective effects on human keratinocytes consistent with repair-oriented topical uses [78]. Applications concerning animal health, antimicrobial stewardship, and agroecological systems are discussed separately in Section 8, which focuses on biotechnology and circularity.

Key bioactive compounds derived from *T. molitor* and their associated health effects are summarised in Table 2 for clarity and cross-reference.

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	Reference
Cryptides (2–20 AA)	Antioxidant, anti-inflammatory	[56]
YAN	Antihypertensive	[61,69]
Hydrophobic fractions	Cardiovascular protection	[18]
LPDQWDWR, APPDGGFWEWGD	Type 2 diabetes	[64]
VVYPWTQ, AWYGANK, LWDHKV	Antihypertensive	[40]
Defatted larval extract	Cardioprotective, anti-inflammatory	[70]

DPP-IV inhibitors	Type 2 diabetes	[72]
Glycosides & heterocycles	Neuroprotective	[74]
Alcalase hydrolysates (standardized process)	Antioxidant; antimicrobial vs. <i>S. aureus</i> , <i>E. coli</i>	[60]
WLNSKGGF, GFIPYEPFLKKMMA	Antimicrobial candidates prioritised in silico; validation pending	[66]
Protein hydrolysates (time-resolved)	Increasing antioxidant capacity during hydrolysis	[5]
Fermented hydrolysates (<i>L. plantarum</i>)	Anti-inflammatory; improved GI motility (mouse)	[73]
Phenolic compounds (methanolic extracts)	Antioxidant (DPPH, FRAP)	[75]
Dermocosmetic peptides (review)	Anti-ageing, moisturizing, soothing (skin)	[76]
Trypsin hydrolysates (in vivo, dermatitis)	Atopic dermatitis amelioration (TLR-MyD88-MAPK)	[77]
<i>T. molitor</i> oil (keratinocytes)	Moisturizing; cytoprotective for skin repair	[78]

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 [79]. 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 [80]. 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 [48]. 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). In short, beans worked, strawberries less so. The key message is that even modest processing can strongly change both growth outcomes and nutritional profiles [81]. In an arid-zone case study in Biskra (Algeria). Larvae were reared on downgraded dates and compared with vegetable scraps. In this pilot study, larvae completed development with comparable growth outcomes [82]. Although the trial was small-scale, it suggests a practical point. Where water and energy are scarce, locally available residues can sustain *T. molitor* rearing without sophisticated equipment.

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 $\approx 4.5\%$ N, 2.6% P, and 2.5% K, together with calcium ($\sim 2.4\%$), magnesium ($\sim 0.8\%$), and trace elements such as Zn, Cu, and Fe. They also noted that residual chitin fragments can “wake up” beneficial soil microbes. 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 [83]. 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 $\sim 65\%$; activity remained stable for several days [84]. In parallel, anaerobic digestion studies reported biogas outputs of 44-668 m³ ton⁻¹ VS and methane yields of 26-502 m³ ton⁻¹ VS, placing them within the range of livestock manures [85]. 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 m²/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 [86].

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 [87]. 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 [5,31,44]. 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 [45].

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 [88]. 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 [89]. 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 [87].

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 [90–92]. One study reported antibacterial effects of insect chitosan against *Pseudomonas aeruginosa*, pointing to possible agro-industrial and biomedical uses [93]. 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 [59].

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 [94]. Furthermore, in food applications, South Korean studies [95,96] 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 [48,80,82]. In addition, dairy by-products such as mozzarella whey and whey permeate have been successfully upcycled, with larvae showing increased protein content ($\approx +7\%$) and favourable fat composition [97]. 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 [87].

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 [98]. Nutritional co-substrates such as lysine and methionine further enhance degradation efficiency [99]. Enzymes such as feruloyl esterase-like PETases isolated from larvae confirm the direct enzymatic potential of this system [100]. 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 [65]. 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 [101]. A similar outcome was noted when phytochemicals forced *T. molitor* to reshape its digestive and detoxification enzymes, which required adjustments in its enzymatic toolkit [102]. 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) [103]. 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 [104]. *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% [105].* 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 [50]. *In that study, feed conversion improved and intestinal morphology showed favourable changes [50].* 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 [106]. 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 [107–109]. 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 [110], while co-feeding strategies improve larval survival under otherwise suboptimal diets [111]. 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 [4,112,113]. 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 [67]. 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 [42]. 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.

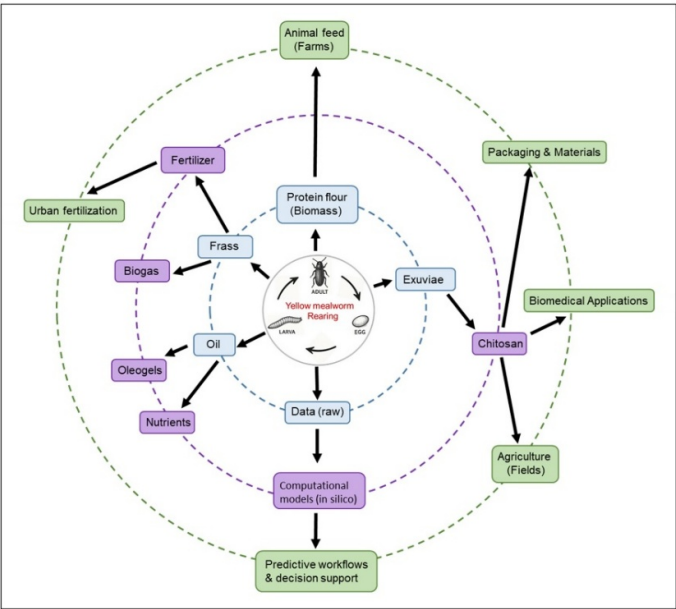


Figure 1. Integrated modular biorefinery for *T. molitor*. Center: rearing and life cycle. Ring 1: primary outputs (protein flour, oils, exuviae). Ring 2: intermediate valorisation (fertiliser, biogas, oleogels, chitosan, in-silico data). Outer nodes: territorial uses (urban fertilisation, animal feed, 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 [36,87]. 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 [36,114]. 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 [115,116]. 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 [117]. 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 [68]. 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 [46]. 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 [103,104]. 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 [5,52].

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 [21]. 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 [115,116]. 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.

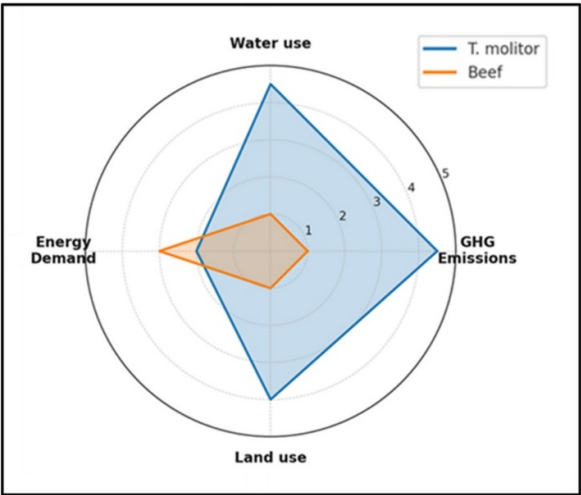


Figure 2. Comparative environmental performance of *T. molitor* and beef (illustrative). Radar diagram based on life cycle assessment (LCA) results. Axes cover greenhouse gas (GHG) emissions, water use, energy demand, and land use. *T. molitor* shows lower impacts in GHG emissions, water, and land use, 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 [12,115].

Table 3. Cross-sectoral opportunities for *T. molitor*.

Application Domain	Valorized Form of <i>T. molitor</i>	Function / Benefit	References
Medical / Biomaterials	Chitin nanofibrils	Skin regeneration, tissue engineering	[4,112,113,116]
Agriculture	Frass, chitosan	Organic fertilizer, soil enhancer, crop protection	[5,14,18,32,33,42,48,79,119]
Animal Nutrition	Meal, peptides	Alternative protein source, gut health, immune modulation	[9,15,48–50,106,120]
Green Biotechnologies	Chitosan	Biodegradable antimicrobial films	[42,107–109]
Food Technology	Oil, oleogels	Fat replacement, nutrient-rich oil	[45,94–96]
Industrial Processes	Whole larvae, oils, meal	Sensor-based monitoring, scalability, optimization	[36,45,87,114,115,117]
Bioinformatics & Predictive Workflows (Transversal)	Proteome mining, in silico modeling	Bioactive-peptide prediction; by-product upcycling; computational workflows	[65,67,68]

Scope note: Table 3 highlights cross-sectoral, non-nutraceutical applications. Rows focused solely on human nutraceutical peptides (covered in Section 6) are excluded. Biomaterials and dermocosmetic uses remain in scope when their function comes from material properties (e.g., chitin nanofibrils), not from ingestible peptides.

9. Conclusions

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. This multi-stream valorisation supports applications across feed, food innovation and co-products. In addition, chitin-derived materials open routes toward biomedical and dermocosmetic uses that are already discussed in the review [4]. Feed applications appear the most deployment-ready. However, this holds only when diet formulation, hygiene and batch consistency are controlled. Food and functional ingredients also look promising. However, most reported bioactivities remain preclinical and often rely on concentrations unlikely to be reached through normal diets. Translation therefore depends on standardised processing, robust safety and quality control, and clear evidence on bioavailability and efficacy in controlled human studies.

A key constraint across the literature is reproducibility. Results can shift with substrate choice, processing conditions and analytical protocols. This directly affects comparability across studies and the credibility of agricultural or health claims. Sustainability outcomes are shaped by a practical trade-off. Industrial systems deliver stable outputs but concentrate infrastructure, process control, and compliance requirements. Low-input systems can fit resource-constrained and arid settings, but they face variability, labour intensity and standardisation limits. Overall, *T. molitor* is a credible component of the circular bioeconomy. However, durable impact requires reproducible methods, realistic positioning and evidence that moves beyond proof of concept. The key message is simple. The sector is ready to scale selectively where quality control and markets are aligned. However, claims should not be generalised without stronger standardisation and validation.

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Materials and Methods: Literature scope and selection. This narrative review synthesizes peer-reviewed literature from 2020 to 2025 on *T. molitor* for food, feed and co-products. It focuses on scale-up constraints and low-input arid-zone models. Earlier landmark work is cited for context, however it was not part of the update window.

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