






EDITORIAL

## Diversifying the promise of insect agriculture

C.J. Picard<sup>1,2\*</sup> , H.R. Jordan<sup>2,3</sup>  and J.K. Tomberlin<sup>2,4</sup> 

<sup>1</sup>Department of Biology, Indiana University Indianapolis, 723 W Michigan Street, Indianapolis, IN 46202, USA; <sup>2</sup>NSF I/UCRC Center for Insect Biomanufacturing and Innovation (CIBI), 2475 TAMU, Texas A&M College Station, TX 77843, USA; <sup>3</sup>Department of Biological Sciences, Mississippi State University, PO Box GY Mississippi State, MS 39762, USA; <sup>4</sup>Department of Entomology, Texas A&M University, 2475 TAMU, College Station, TX 77843, USA; \*cpicard@iu.edu

Published online 4 December 2025 |

Published in issue 5 January 2026

### Abstract

Over the past decade, insect agriculture has evolved from a focus on protein production to a broader vision of insects as sustainable biomanufacturing platforms. Once hindered by regulatory, cultural, and economic barriers, the field has emerged stronger through innovation and diversification. Insects now represent powerful tools for biotechnology, bioremediation, and soil enhancement, offering solutions to global challenges such as pollution, food security, and climate change. As living bioreactors, they enable medical and agricultural innovation, though ethical and ecological safeguards remain essential for sustainable advancement.

### 1 Introduction

A decade ago, the promise of insect agriculture was defined largely by its potential to produce protein and fat (van Huis, 2013; Van Huis, 2020; van Huis et al., 2015; Van Huis et al., 2021). Today, the narrative has evolved, becoming richer and far more revolutionary. Early enthusiasm fuelled substantial investment, but as the industry matured, it encountered significant hurdles matched with as many opportunities (Lalander et al., 2025). Substrate sourcing, production costs, and cultural resistance have slowed progress in many parts of the world, but these challenges have also streamlined processes within the sector, encouraging strategic innovation and long-term thinking. These setbacks were often interpreted as signs that the industry's viability was in doubt. Yet, rather than signalling failure, these pressure points have served to refine and reshape the field, steering it towards new opportunities and a more resilient future globally. Diversifying insect-based products is not just an economic imperative – it is a way to address food security, climate change, resource

limitations, and other major global issues. Insects are poised to become biomanufacturing workhorses, capable of generating a diverse array of value-added products (Najar-Rodriguez and Picard, 2025). This shift from a narrow focus on protein to a broader vision of insects as versatile biomanufacturing platforms sets the stage for exploring their future role.

#### *Insects as Efficient, Sustainable Bioreactors*

Insect-derived products are on the cusp of becoming a major industry, but realising their full potential requires a shift beyond traditional protein-centric thinking. Insects possess a remarkable repertoire of biological processes and adaptations, offering opportunities for innovation across biotechnology, agriculture, and environmental management. Rather than reinventing the wheel, we can study and apply naturally occurring insect mechanisms to address diverse challenges.

The adaptability of insects in general is unparalleled: they thrive in a wide range of environments and efficiently convert low-value materials into nutrients. This evolutionary resilience, which evolved over millions of

years, is now accessible to us through modern scientific tools. Historically, insects have served humanity in many ways: producing silk and honey (Chand et al., 2021; Cherry, 1987), acting as biocontrol agents (van den Bosch et al., 1982), and even serving as pets (Ko et al., 2016). More recently, the food and feed industry has recognised their efficiency in transforming resources into protein, fat, and valuable byproducts like frass (Poveda, 2021).

This framework indicates the need to diversify insect-based products, not solely for economic reasons, but to address smaller issues while contributing to broader challenges such as food security and climate change. It is not necessary to focus exclusively on alternative proteins for animal feed at present. Instead, insects can be leveraged as models for biomanufacturing systems, with each component offering potential value beyond only protein production.

Furthermore, insects are great models for discovering unique mechanisms for industrialised production of materials of value. Such discoveries are due in part to the advantages insects provide researchers that vertebrates do not. They are fast to develop, easily maintained, and can be replicated in high numbers. However, the insects as food and feed sector appears to have garnered much attention recently due to the need for greater enhancement of the bioeconomy. That said, the industry is now positioned to diversify and expand its value to humanity globally by developing partnerships within the biotechnology sphere. Such a bridge could result in a network of discoveries that expand the value of the insect agriculture sector, which could in turn reduce the cost of producing these insects and their associated products. Beyond their role in biomanufacturing, insects also offer remarkable solutions for environmental challenges.

#### *Bioremediation and Simultaneous Value-Cycling*

Insects offer a powerful advantage in the field of environmental biotechnology, representing an industrial model for value-cycling. This unique dual-purpose approach achieves both primary goals: targeted bioremediation (the breakdown of pollutants) and bioconversion (the upcycling of low value inputs to valuable products). The high efficacy of this system is fundamentally rooted in the insects' digestive tract, which acts as a specialised host-microbe degradation system.

This remarkable capacity also includes the sequestration of heavy metals and toxins. Insects, aided by their gut microbiomes, can transform, sequester, or bioaccumulate contaminants such as cadmium, lead, and per-

sistent organic pollutants. Specialised gut bacteria bind, chelate, or chemically alter these substances, reducing their toxicity before absorption (Khan and Lang, 2023; Li et al., 2024; Pande et al., 2022). As a result, pollutants are concentrated in the insect's chitinous exoskeleton, effectively isolating them and making edible insect-derived products safer.

The ability of insects to break down complex organic or toxic substrates, such as lignin, cellulose, and notably plastics and recalcitrant pesticides, is not intrinsic to the insect alone (Vital-Vilchis and Karunakaran, 2025; Yang et al., 2024). Rather, it is a symbiotic partnership wherein the gut microbes produce highly efficient enzymes (such as cellulases, laccases and chitinases) that initiate the depolymerisation process, which the insect then completes. In essence, the insects serve as contained, mobile 'bioreactors' that cultivate and concentrate these powerful microbial agents, offering a more effective and contained system than traditional open-air microbial remediation. The bioremediation process also produces chitin, a valuable by-product extracted from the exoskeleton. Chitin and its derivative, chitosan, are used in bioplastics, medical applications, and biopesticides, ensuring that every part of the insect remains an economic asset.

This dual-function capability makes insects ideal for cleaning up pollution hotspots, such as SuperFund sites and industrial sludge, and even for space or off-World bioregeneration, thanks to their small footprint and closed-loop potential. While bioremediation highlights the environmental promise of insects, their impact extends further – their byproducts, such as frass, pave the way for advances in soil enhancement and agricultural innovation.

#### *Soil Enhancement via Genetic and Microbial Modification*

The residual product of bioconversion, insect frass, is far more than just a residual by-product. It is a critical component of the value proposition, with potential to act as a powerful biostimulant. Frass serves not only as a nutrient-rich fertiliser but also as a diverse microbial inoculant. This microbial activity, derived from the insect gut and substrate, acts as natural soil probiotics for plants, improving nutrient cycling, pathogen suppression, and soil structure (Athanassiou and Rumbos, 2025). Furthermore, insect exuviae as well as residual chitin fragments in the frass could act as soil and plant immune system activators, priming crops for better resistance to pests and pathogens (Rumbos et al., 2025). Chitin is generally chemically stable under heat

treatment at temperatures well above 70 °C, ensuring its bioactive properties are preserved. To optimise frass quality, targeted substrate inoculation can be applied by supplementing the rearing substrate with specific, well-characterised microbial strains. In instances where heat treatment is necessary, beneficial microbes can be introduced after processing. This approach serves two key purposes: (i) enhancing the nutritional quality of the substrate; and, (ii) guaranteeing that the resulting frass contains beneficial microbes while actively suppressing potential human, animal and plant pathogens present in the feedstock.

Additionally, targeted bioremediation could be optimised by developing genetically modified insect strains optimised to break down specific, difficult-to-degrade pollutants, such as per- and poly-fluoroalkyl (PFAS) substances or certain recalcitrant pesticides, ensuring their safe sequestration away from the edible biomass.

While it has been established that chitin has pesticidal properties, its underlying mechanisms remain poorly understood. Addressing such knowledge gaps will require multidisciplinary collaboration – with plant physiologists, microbiologists, and entomologists – to elucidate how changes in soil and root microbiomes influence plant expression (e.g. volatile emissions or protective measures) and, in turn, how insects respond to these cues. Questions remain around the signalling mechanisms – for instance, whether chitin signals high insect density, leading to resource avoidance, and which odours, receptors, and proteins modulate insect behaviour accordingly. Advancing basic research in these areas will spur innovation in pest management, focusing not only on new insecticidal compounds but also on defensive strategies that safeguard crops without harming beneficial insects.

### ***Insects as Platforms for Medical and Agricultural Innovation***

With at least five million insect species, it is clear that relying solely on *Drosophila melanogaster* (Diptera: Drosophilidae) as a model barely scratches the surface of insect diversity and potential applications (Stork, 2018; Stork et al., 2024). Recent advances in biotechnology and molecular tools have made it easier and more cost-effective to manipulate a wide range of insect species, allowing researchers to both uncover their unique biological functions and enhance desirable traits such as growth rate and product yield.

Dipteran larvae, for example, represent particularly valuable models for genetic manipulation due to exploitable natural temporal processes. For instance, as

dipteran larvae grow, they produce increased metabolic heat, activating molecular mechanisms – such as heat shock proteins – that regulate temperature (Banfi et al., 2025). By leveraging these promoters, scientists can modulate the expression of target genes through temperature shifts. Light responsive promoters further expand options for precise control for generating nearly any biological target.

Modern systems allow insects to serve as living bioreactors, synthesising proteins or small molecules for medical or agricultural use. Following extraction, the remaining biomass can be repurposed, maximising resource efficiency. In medicine, insect-based platforms already produce vaccines, some edible, others requiring processing, and continue to hold great promise for novel antimicrobial peptides (Crisuolo et al., 2019). Beyond production, these may serve as unique models for exploring previously uncharted areas of pharmacology and disease biology. Many dipterans diverged from *Drosophila* over 100 million years ago, thus granting access to genes that may be absent in traditional models and opening new avenues for discovery.

On the agricultural front, scaled insect production systems provide unique opportunities as real-world test beds for pest management strategies, enabling resistance monitoring and survival mechanism studies. Their diversity also supports comparative studies on variation in phenotypic and pharmacological responses, improving predictive power for both crop protection and human health applications.

But how can we ensure these innovations are safe and sustainable? This brings us to the ethical considerations of insect biotechnology.

### ***Potential Risks and Ethical Considerations***

The deployment of advanced insect biotechnology must be accompanied by rigorous assessment of ethical and ecological risks. The use of genetically modified systems introduces the risk of horizontal gene transfer, where engineered genes in the insect's gut bacteria could transfer to native environmental microbial communities, leading to unpredictable ecological effects. Furthermore, the challenge of bioaccumulation and product safety must be addressed through stringent regulation. If insects are used to sequester heavy metals or toxins, clear end-goal regulatory pathways are needed to ensure the disposal of any highly contaminated protein/fat biomass and frass (e.g. the chitin from heavy metal remediation) to ensure that it does not end up in the food chain or agricultural soil. Finally, traditional ecological risks, such as invasive species risk

(e.g. escape), must be mitigated through the development of 'fail-safe' strategies, such as self-limiting genes or sterile strains, to prevent the unintended disruption of local ecosystems. This rapid industrialisation and genetic refinement also necessitate a robust discussion of insect welfare and sentience alongside the economic benefits (Lalander et al., 2025).

### ***Conclusion: The Path Forward***

The significant opportunities presented by insects are both vast and evident. Over the past thirty years, we have witnessed impressive capabilities among various species, and current advancements are just the beginning. With more than five million different species available for diverse applications, the potential for innovation in this field is immense. Each insect brings unique value. Thus, it is essential to prioritise responsible innovation and foster public engagement as we envision the future role of insects in biotechnology.

### **Acknowledgement**

This material is based upon work supported by the National Science Foundation under Grant Nos. 2052565, 2052788, 2052454. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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