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EDITORIAL

Working out the bugs: navigating challenges and unlocking opportunities in the insect industry

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Abstract

In 2013, the United Nations Food and Agriculture Organization identified insects as a promising solution for sustainably feeding the world's growing population. However, despite a decade of development and innovation, the insect industry has yet to fully realize its environmental and economic potential. This review takes an evidence-based approach to addressing key challenges in the sector, including integrating circular production systems within existing regulatory frameworks in the Global North, ensuring product safety in circular systems, assessing allergen risks associated with insect-based products, mitigating biosecurity risks linked to non-native insect species, evaluating the environmental safety of insect by-products, and promoting animal welfare in insect production. While significant challenges remain, the evidence presented highlights how further research can help unlock opportunities for the industry to achieve its full potential globally. Ultimately, we argue that overcoming challenges – 'working out the bugs' – is a fundamental step in the evolution of any emerging industry. Furthermore, greater support for the transition to circular economies will accelerate the sector's ability to generate meaningful environmental, ethical, and economic benefits.

1 Introduction

The necessity of implementing a bioeconomic model for the sustainable production of food and feed has been recognized globally, as reflected in the United Nations Sustainable Development Goals (SDGs) – specifically Goal 2 (Zero Hunger) and Goal 12 (Responsible Consumption and Production) – and the European Green Deal (European Commission, 2020). However, there is still considerable debate about the most effective strategies for transitioning to this new agricultural paradigm (Allain *et al.*, 2022). Agricultural practices in any given location are interconnected such that changes made in one aspect of the system can induce cascading effects throughout the broader agroecosystem (Walsh *et al.*, 2024). Similarly, approaches aimed at achieving a bioeconomic transition are not universally applicable as each region faces distinct environmental, economic, and social conditions. As a result, efforts to minimize environmental impact in one context may not be directly transferable to others, complicating the development of a unified, agreed-upon pathway for transition. The lack of consensus on the optimal methods for implementation, combined with a limited understanding of their broader ecological and socioeconomic implications, further exacerbates the uncertainty surrounding the best approach(es) to achieving a sustainable bioeconomic shift.

Incorporating insects as food and feed into our agricultural system represents a relatively novel bioeco-

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nomic approach to promoting greater circularity in the food chain (Hamam *et al.*, 2024). Implementing this circular technology into the current linear mode of production poses significant challenges, especially considering the role of insects in linking environmental sustainability with waste management and food production. Challenges faced by this industry thus exemplify the lack of consensus in transitioning to a bioeconomic model, as the sector is shaped by cultural, social, and economic factors on a global scale, while the environmental impact of insect-based systems varies significantly depending on their implementation (Govorushko, 2019; Traynor *et al.*, 2024).

This article aims to present a global perspective on the challenges and opportunities within the insects as food and feed industry, highlighting how its implementation may vary based on regional contexts.

2 Is insect production truly circular?

Many insect species have demonstrated the ability to process a wide range of organic wastes, converting them into high-value products such as protein-rich feed, oils, and organic fertilizers, while reducing the volume of organic waste by up to 75% (Gold *et al.*, 2018). The larvae of the black soldier fly (BSFL; *Hermetia illucens* L., Diptera: Stratiomyidae) can be reared on an especially wide range of substrates, including swine, dairy and poultry manures (Hoek-van den Hil *et al.*, 2023; Li *et al.*, 2011; Zhao *et al.*, 2023), and human waste (Banks *et al.*, 2014; Lalander *et al.*, 2013), though with varying efficiency. These materials, which have limited economic value and pose environmental risks, can be effectively recycled using insects – mitigating these risks, generating economic value, and contributing to a more circular agroecosystem, a potential supported by a substantial body of research (Amrul *et al.*, 2022; Beesigamukama *et al.*, 2023; Ganesan *et al.*, 2024; Hoffmans *et al.*, 2024; Ogbon *et al.*, 2025; ur Rehman *et al.*, 2025).

However, some critics argue that the potential circularity benefits of the insect industry are not realized as producers may feed insects substrates that could otherwise be used directly as animal feed, rather than utilizing food waste or other previously mentioned waste streams (Biteau *et al.*, 2025). At present, some industrial insect farms in Global North nations do utilize feed-grade materials. However, this practice is primarily driven by regulatory constraints, rather than being an inherent limitation of insect farming itself (Bosch *et al.*, 2019). These regulations are largely a consequence of the 1990s outbreak of Bovine Spongiform Encephalopathy (BSE; commonly referred to as mad cow disease) which prompted the establishment of stringent feed safety regulations in the European Union (EU), including the prohibition of feeding certain animal-derived materials back into the food chain to prevent disease transmission (Vågsholm *et al.*, 2020).

Currently, insect producers in the EU are restricted to substrates that are already approved for feeding livestock, such as vegetable waste and cereal by-products (European Commission, 2022). This precautionary approach – driven by ethical and social imperatives to ensure food and environmental safety – has not only restricted the potential for insects to function as large-scale biowaste recyclers, thus contributing to the transition to a bioeconomic model (Ohja *et al.*, 2020), but it has also slowed the adoption of circular systems more broadly (Calisto Friant *et al.*, 2021; Försterling *et al.*, 2023), thus limiting the realization and expansion of this industry's potential as a fully circular system (Lalander and Vinnerås, 2022). However, the situation may be shifting as regulatory frameworks continue to evolve in line with the European Green Deal and as additional data on product safety are collected (further details are presented in a subsequent section). Following approval of processed insect protein for aquaculture in 2017 (Commission Regulation (EU) 893/2017) and for pig and poultry feed in 2021 (Commission Regulation (EU) 2021/1372) (IPIFF, Vision paper), there has been growing advocacy for expanding substrate options, particularly those derived from former meat and fish products as well as catering waste.

It is essential to recognize that regulations in the EU, Canada, and the United States of America (USA) do not necessarily apply universally, due to differences in perception, infrastructure, and/or economic priorities across different regions. In the Global South – an area including Africa, Asia, and Central and South America – producers may not be subject to the same regulatory constraints on insect feed, or there may be a lack of clarity regarding permissible substrates for insect-rearing. Some stakeholders in these regions voluntarily adhere to EU legislation to facilitate exports (Barragán-Fonseca *et al.*, 2024). As domestic markets for insect protein continue to expand, national regulations in Global South countries may increasingly shape local insect feed practices rather than regulations set by export markets. These regulations may diverge from those in the Global North nations; however, enabling nations to develop independent regulatory structures is crucial for self-governance (Bukchin-Peles *et al.*, 2025). Such autonomy can support the development of infrastructure for recycling low-value waste, which is currently poorly managed (or not managed at all) posing significant risks to human health and the environment (United Nations Environment Programme and International Solid Waste Association, 2024). Industrial diversification in this sector can stimulate economic growth, strengthen community resilience and promote environmental sustainability while reducing reliance on imports (Barragán-Fonseca *et al.*, 2024; Bukchin-Peles *et al.*, 2025).

3 Can we ensure safety in circular insect production systems?

If insects are reared on waste substrates and subsequently reintroduced into the food chain as food or feed, the process becomes inherently circular. However, circular systems pose greater safety risks than linear systems, primarily due to the potential for accumulation of chemical or biological contaminants (Focker *et al.*, 2022): as materials circulate, persistent compounds that are not degraded may build up over time.

A significant safety concern in circular food systems is the presence of prions, which were responsible for the BSE outbreak (Vågsholm *et al.*, 2020). Prions (PrP^{Sc}) are infectious, misfolded forms of the cellular prion protein (PrP^{C}), which is encoded by a chromosomal gene and is commonly expressed in the human nervous system (Prusiner, 2001). Once introduced, PrP^{Sc} induces the misfolding of PrP^{C} into additional PrP^{Sc}, leading to the accumulation of PrP^{Sc} in the brain and the development of transmissible spongiform encephalopathies (TSEs), also known as prion diseases. Prions are highly resistant to conventional sanitization treatments, requiring inactivation at 133 °C at 3 bar pressure as opposed to the standard 70 °C for 1 h commonly used for other pathogens (Ducrot *et al.*, 2008). Given that food waste proteins may become concentrated in insect biomass, it is critical to assess whether insects can acquire prions from their feed or act as mechanical vectors.

Unlike mammals, insects lack a homologous gene for PrP^{C}, suggesting that they are unlikely to act as biological hosts or amplifiers of prions (EFSA Scientific Committee, 2015). However, Benestad *et al.* (2024) demonstrated that BSFL could harbour detectable prions when immersed in and fed high doses of prion-infected substrate. Notably, prions were only detected using the highly sensitive, Protein Misfolding Cyclic Amplification (PMCA) assay, whereas standard detection methods such as ELISA and Western blot failed to identify prions without the amplification step. Since PMCA is up to 3 billion times more sensitive than standard immunoblotting techniques and 4000 times more sensitive than animal bioassays, it may overestimate prion presence (Wang *et al.*, 2023). Additionally, Benestad *et al.* (2024) pointed out that the BSFL were exposed to unrealistically high prion concentrations (pure infected brain tissue), whereas any prions present in food waste would be highly diluted. The study also did not optimize BSFL bioconversion conditions, which could influence prion degradation.

Some *in vitro* studies suggest that prions can be reduced by microbial populations and enzymatic activity: *e.g.* research on ruminant digestion indicates that prions can be degraded, potentially due to microbial action (Scherbel *et al.*, 2006) or digestive enzymes and physicochemical conditions in the gastrointestinal tract (Jeffrey *et al.*, 2006). Additionally, specific enzymes such as the thermostable protease Tk-SP from the archaeon *Thermococcus kodakarensis* (Hirata *et al.*, 2013) and keratinase from *Bacillus licheniformis* N22 (Okoroma *et al.*, 2013) have been demonstrated to degrade prions under certain conditions. Since BSFL bioconversion involves high biological activity, including microbial communities and enzymatic processes (Gold *et al.*, 2020), prion degradation in the BSFL bioconversion process may occur under optimized conditions. Further research is necessary to determine the fate of prions in optimized insect production systems and asses the realistic risk of prion-contaminated substrates being used as feed. Furthermore, it is important to determine the likely risk of insects having access to prion-contaminated feeds, which depends on which waste substrates are used. Prions are primarily associated with the central nervous system tissue of infected animals (Brown *et al.*, 2001). Their presence in food and catering waste is thus unlikely, as these tissues have to be removed from the human and animal food chain according to both EU (Regulation (EC) No 999/2001) and US regulations (9 CFR para. 310.22) (European Commission, 2001; United States Department of Agriculture (USDA), 2021).

Beyond prions, concerns exist regarding bacterial, viral and fungal pathogens in insect bioconversion systems. Several studies have demonstrated that *Salmonella* spp., a zoonotic pathogen, is inactivated during BSFL bioconversion (Erickson *et al.*, 2004; Lalander *et al.*, 2013, 2015, 2025; Lopes *et al.*, 2020). However, when BSFL are reared in high moisture substrates with excessive bacterial loads, *Salmonella* spp. can persist in the larval gut (Lalander *et al.*, 2013; Ogbon *et al.*, 2025). Other pathogens, including *Escherichia coli*, and animal viruses such as adenovirus, reovirus and enterovirus, are also reduced to varying degrees through BSFL bioconversion (Erickson *et al.*, 2004; Lalander *et al.*, 2025; Lopes *et al.*, 2020).

Insects possess a diverse array of antimicrobial peptides (AMPs) with antibacterial, antifungal and antiparasitic properties (Mylonakis *et al.*, 2016; Stączek *et al.*, 2023). This has led to growing interest in utilizing insect-derived AMPs to combat antimicrobial resistance (Azmiera *et al.*, 2022). BSFL, in particular, produce a broad spectrum of AMPs. Van Moll *et al.* (2022) found that BSFL-derived AMPs could inactivate *in vitro* several human pathogens, including *Staphylococcus aureus*, *E. coli*, *Candida albicans*, *Klebsiella pneumoniae*, *Aspergillus fumigatus* and multidrug-resistant *Pseudomonas aeruginosa*. However, some pathogens and parasites, such as *Ascaris suum* eggs, are not inactivated by BSFL bioconversion alone (Lalander *et al.*, 2013; Lalander *et al.*, 2015). Therefore, additional sanitation methods, such as the EU-mandated 70 °C heat treatment for 1 h (Reg. 142/2011), are necessary to ensure safety.

Toxicological risks in circular insect systems include the potential accumulation of mycotoxins and bacterial toxins. Aflatoxin B1, a regulated mycotoxin (EC 1881/2006) commonly found in seeds and nuts, is metabolized to varying degrees in insects depending on concentration and larval stage (Niermans *et al.*, 2021). This suggests that insect farming could be used for mycotoxin remediation. Among bacterial toxins, botulinum neurotoxins (BoNTs A-G), from *Clostridium botulinum*, are a concern due to the resistance of spores to extreme conditions (Caya, 2001). While no studies have yet examined *C. botulinum* in insect rearing, Van Looveren *et al.* (2022b) found that *Clostridium perfringens* spores remained viable after 1 h at 70 °C in an industrial BSFL facility, although bacterial levels were undetectable in the larvae. Alagappan *et al.* (2025) showed that thermal processing of BSFL reared on food waste effectively reduced *E. coli*, *Salmonella* spp., and *Listeria monocytogenes*, but only partially reduced *C. perfringens*, and they highlighted the need for further safety measures.

Pharmaceutical residues, including antibiotics, as well as pesticides, such as fungicides and insecticides, have been shown to degrade during the BSFL bioconversion process (Lalander *et al.*, 2016; Liu *et al.*, 2021; Meijer *et al.*, 2021; Purschke *et al.*, 2017). Liu *et al.* (2020) demonstrated that oxytetracycline, a prevalent residual antibiotic in the environment, degrades in BSFL bioconversion. However, they also emphasized the need for further investigation into the potential dissemination of antimicrobial resistance genes and mobile genetic elements formed in the process.

Heavy metals can bioaccumulate in insect biomass, depending on the rearing substrate. In a systematic review, Malematja *et al.* (2023) reported the bioaccumulation of cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), zinc (Zn), copper (Cu), and iron (Fe) in various insect species, with Cd and Pb often exceeding regulatory limits. Substrate management is crucial in mitigating these risks. Studies have confirmed that BSFL reared on European former foodstuff accumulate Cd and mineral oils, though within EU legal limits (van der Fels-Klerx *et al.* (2020)). Similarly, Ogbon *et al.* (2025) found Cu, chromium, Cd, Pb, and Zn in BSFL reared on biowaste in Benin, but at levels below recommended limits. Effective upstream management of substrates will be essential to mitigate any risks associated with heavy metal accumulation in circular systems that include insects.

Importantly, these safety concerns primarily apply when insects are used for food, feed, or pharmaceuticals. However, insects have additional applications in sustainable packaging, biofuels and other industrial sectors where possible contaminations are less of a concern (Bruno *et al.*, 2025). This raises the potential for insects to be used in entomo-remediation – biodegrading or bio-transforming contaminated substrates unsuitable for food and feed into value-added industrial products.

4 Can insects cause allergies when used as food or feed? What about chitin?

Chitin is a naturally occurring polymer primarily found in the exoskeletons of arthropods, such as insects and crustaceans, as well as in certain fungi (Muzzarelli, 2011). It is the second most abundant biopolymer after cellulose and is classified as a fibrous polysaccharide (Yu *et al.*, 2020). Chitin is resistant to enzymatic breakdown in the human stomach but undergoes microbial fermentation in the colon (Wang *et al.*, 2019). Its deacetylated derivative, chitosan, is more soluble in the alkaline environment of the small intestine and is more susceptible to enzymatic degradation (Wijesekara and Xu, 2024).

Although mammals cannot synthesize chitin endogenously, they produce two active chitinases capable of degrading chitin (Hellmann *et al.*, 2025). While research into these enzymes largely focused on their role in allergic airway diseases, there remains debate about whether they simply serve as biomarkers or play an active role in disease pathogenesis (Declercq *et al.*, 2023). According to Cunha *et al.* (2023) the presence of chitin in insect-based products may lead to slower digestion and delayed release of the amino acids contained in chitin.

Despite some concerns, chitin and its derivate chitosan have been associated with various beneficial health effects. These include anti-inflammatory properties, modulation of the immune system, cholesterol reduction, and antimicrobial activity, especially in relation to gut health (Stull and Weir, 2023; Wijesekara and Xu, 2024). In a 13-week study conducted by the European Food Safety Authority (EFSA), rats were administered chitin at a dose 80 times higher than the intended human intake, with no adverse effects observed (EFSA Panel on Dietetic Products and Allergies, 2010).

Although chitin is generally considered safe, a systematic review of studies conducted over a ten-year period highlighted cross-reactivity as a significant concern for food safety when consuming edible insects (Cunha *et al.*, 2023). Cross-reactivity between insect allergens and known allergens, such as those in shrimp and house dust mites, was noted. Tropomyosin and arginine kinase, two proteins common in invertebrates, were identified as major pan-allergens. While food-processing techniques can reduce cross-allergenicity, the effectiveness of different techniques varies. Little is known about allergens in insects used as feed, although Bose *et al.* (2022) identified 33 potential allergens in BSFL. Given the risk of allergic reactions in humans or pets, EU legislation (Law No 411/2023) mandates allergen warning on products containing insect-based ingredients, like other potential allergens.

In addition to concerns about food allergies, individuals working with insects may be at risk for occupational allergies, such as skin rashes and respiratory issues, due to prolonged exposure to insect-derived products. Crickets (Orthoptera), mealworms (Coleoptera), and cockroaches (Blattodea) are particularly likely to trigger allergic reactions in workers as they can produce airborne particles (Gasco, pers. comm.). As with other environmental health and safety risks, legislation, hygiene practices, ventilation, personal protective equipment and proper training can help minimize exposure and reduce the likelihood of serious occupational allergies.

5 Does the farming of non-domestic species, or endemic species in large numbers, pose a human or environmental risk?

When considering the farming of non-domestic insect species, it is essential to evaluate whether the introduction of that species into a new environment presents potential risks to human health or the broader environment, including biodiversity. This assessment is contingent upon determining whether the introduced (non-native) insect species is classified as a 'quarantine pest'. To ascertain this, both national and international regulatory authorities must perform a thorough risk assessment. This process involves assessing the likelihood of the farmed, non-endemic insect species escaping cultivation, surviving in the wild, and potentially causing harm to humans, animals, plants or local ecosystems (van Huis and Oonincx, 2017). Similarly, if endemic insect species escape from farms, they may become a nuisance, *e.g.* house flies, *Musca domestica*, L. (Diptera: Muscidae).

If, following a comprehensive risk assessment of insect farming, a permit is granted, it can generally be assumed that farming the species under specified conditions does not pose significant risks to humans, animals or the environment. For both non-domestic and endemic species, insect-farming permits in the EU often include mandatory containment measures, such as sealing or filtering all openings in rearing facilities to reduce the likelihood of escape (IPIFF, 2024b). Although the BSF – the most-farmed insect species – is not endemic to many areas where it is reared today, it has already established populations in several of these regions long before insect farming became widespread (*e.g.* southern France and the Mediterranean region as a whole) (Maquart *et al.*, 2020). In many other countries where BSF farming is now practised, environmental temperatures remain outside the optimal range of the flies (Chia *et al.*, 2018) for much of the year, making it less likely for any escaped flies to reproduce or establish viable populations. For instance, in north-western Europe, laboratory studies suggest that BSF can survive for an estimated 47 days in winter field conditions; however, at such low temperatures, reproduction is not feasible, making long-term establishment improbable (Spranghers *et al.*, 2017).

6 Are there potential future biosecurity risks with genetically modified insects?

As synthetic biology and other advanced genetic technologies evolve, ethical and governance frameworks must address the increasing possibility of biosecurity risks, including those arising from the accidental release of genetically modified organisms (Bohua *et al.*, 2023). These risks could include the disruption of natural ecosystems, hybridization with native populations and the unintended spread of genetic modifications. Moreover, if genetically modified organisms possess greater resilience, they could potentially cause more severe ecological damage. However, these concerns remain speculative, as there is a lack of research on how farmed insect strains might perform in natural environments. Therefore, thorough risk assessments are necessary for genetically modified insects, like the assessment for non-native species, as outlined earlier (Parent and Barrett, 2024).

These challenges also present valuable opportunities for research into containment strategies, preventing gene flow, and conducting ecological risk assessments. Several containment methods can be integrated into insect breeding to minimize risks. These include kill-switches or self-limiting genes to prevent survival in the wild, engineering dependency on synthetic nutrients not found in nature, and implementing inducible lethality, where exposure to specific environmental conditions (such as particular wavelengths of light activating a sterility gene) can prevent reproduction (Rottinghaus *et al.*, 2022; Wright *et al.*, 2013). Additionally, genetic incompatibility, such as large-scale chromosomal inversions, can be engineered to limit gene flow. Ultimately, developing and validating these innovative biocontainment approaches will be crucial to advance insect biotechnology safely, ensuring environmental protection, and building public trust.

7 Is there a risk to soil and plants when using insect frass as fertilizer?

Insect farming generates significant quantities of a by-product with fertilizing potential known as insect frass (Lopes *et al.*, 2022). According to the EU, frass is a mixture of excrement from farmed insects, feeding substrates, insect body parts, and dead eggs (Reg. 2021/1925). It contains plant nutrients, various microorganisms, and bioactive substances (Barragán-Fonseca *et al.*, 2022; Green, 2023). When applied to soil, insect frass exhibits similar properties to compost or manure, depending on its composition, which can vary based on the insects' feed substrate. For example, mealworms (Coleoptera: Tenebrionidae) are typically fed dry substrates (*e.g.* wheat bran), while BSFL are fed wet substrates (*e.g.* fruit and vegetable waste). Consequently, the physiochemical characteristics of frass from these two species (or even the same species fed different substrates) may differ significantly (Poveda, 2021).

Given the limited range of feed materials approved for insect farming in the EU, the predictability of the bioconversion efficiency, safety and quality of frass is generally high (Lalander and Guidini Lopes, 2024). Although frass, particularly from BSFL, can exhibit slight phytotoxicity (*i.e.* be harmful or inhibit plant growth) this issue can easily be mitigated when the frass is fresh, using technologies such as composting (Song *et al.*, 2021) or frass recirculation (Lopes *et al.*, 2024). With these measures, insect frass can be considered safe for use as a fertilizer or soil improver with no significant risk to soil or plants (Mostafaie *et al.*, 2025). However, when new waste streams are approved as feed substrates in the future, the quality of the resulting frass will need to be monitored. Currently, EU regulations require frass to undergo a heat treatment of 70 °C for 1 h to ensure sanitization (Reg. 142/2011), a procedure proven to effectively ensure biological safety of frass (Van Looveren *et al.*, 2022a). New safety protocols may be needed if novel safety concerns are identified in frass derived from currently unauthorized waste streams.

In essence, insect frass can be viewed as type of organic material comparable to other animal manures. A sanitation process is necessary to ensure biological safety prior to use. Given the need for increased resilience of food and feed production in various regions, insect frass can be a promising alternative to provide nutrients, organic matter, and bioactive compounds, contributing to more sustainable and resilient agricultural systems.

8 Can we promote the welfare of insects farmed as food and feed?

Welfare is defined here affectively, as how an animal is feeling, from its own perspective (Fraser, 2008). Insects can have affective states if they are sentient, a topic around which there is ongoing debate (Adamo, 2019; Barrett and Fischer, 2024; Gibbons *et al.*, 2022). This uncertainty is particularly relevant for larvae, such as BSFL, which make up the majority of animals currently farmed in the insects as food and feed industry (Hancz *et al.*, 2024), numbering in the trillions each year (Barrett and Fischer, 2023). However, the preponderance of neurobiological and behavioural evidence suggests that insect sentience is plausible, especially in adult flies (Diptera) and cockroaches and termites (Blattodea) (Barrett and Fischer, 2024; Gibbons *et al.*, 2022). Where animal sentience is plausible, the precautionary principle recommends that welfare be considered when those animals are used for human aims (Birch, 2024). Accordingly, industry-adjacent academics and industry trade organizations have called for greater attention to the health and welfare of farmed insects (Barrett *et al.*, 2023a; IPIFF, 2022; 2024a; Röcklinsberg *et al.*, 2013; Röcklinsberg, 2017; van Huis, 2021).

Like other animal production systems, insect farming is likely to present welfare challenges. These include non-instantaneous slaughter without prior stunning, larval overheating, inappropriate or missing nutrition, cannibalism, disease (and depopulation), overstocking, and behavioural restrictions (Barrett *et al.*, 2023a; Barrett *et al.*, 2023b; Kortsmit *et al.*, 2023; Rowe *et al.*, 2024). As the industry grows, new welfare challenges may arise, such as emerging diseases or the unintended consequences of selective breeding (*e.g.* health challenges and behavioural restrictions; though genetic tools could also be employed to improve welfare, see Parent and Barrett (2024)). Welfare challenges are often species- and life-stage-specific, and may vary based on specific management practices (Barrett and Fischer, 2023). Therefore, recommendations must be context-sensitive and informed by both scientific evidence and best practices in production.

Some welfare challenges, such as insect health and disease, are already receiving increased attention. Insects, like all living organisms, are susceptible to various diseases, including bacterial, viral and fungal infections as well as infections with other invertebrate parasites (Eilenberg *et al.*, 2015; Joosten *et al.*, 2020). Virulent diseases, such as AdDNV (a virus that affects house crickets (*Acheta domesticus* L.; Orthoptera: Gryllidae)), can lead to the loss of entire insect populations at production facilities (Weissman *et al.*, 2012). The welfare and economic consequences of these outbreaks have led to greater coordination among academics and producers to better understand insect diseases, and a focus on species that appear more robust against diseases (Eilenberg *et al.*, 2015; Joosten *et al.*, 2020; Weissman *et al.*, 2012). Additionally, many of the largest insect farms have implemented rigorous hygiene measures, such as controlled environmental conditions, equipment sterilization, restricted access zones, Hazard Analysis and Critical Control Points (HACCP) protocols, and continuous health monitoring to prevent outbreaks (IPIFF, 2024a; Joosten *et al.*, 2020). Increased integration with the veterinary community, a process currently underway at many facilities, will further improve the management of these 'mini-livestock' over time.

Other welfare challenges that have recently received public attention include the feeding of waste substrates to BSFL and the high stocking densities found in insect production facilities. BSFL are natural recyclers of decaying materials, with digestive and immune systems adapted to a wide range of microbially rich waste sources (Bruno *et al.*, 2021; Ganesan *et al.*, 2024). Many 'waste' sources are thus part of their natural diet. However, caution is needed when interpreting welfare in terms of 'naturalness', as not all natural conditions are beneficial to an animal's affective welfare (textite.g. disease or predation; (Dawkins, 2023)). Nevertheless, BSFL can thrive on a variety of waste streams (Lalander and Guidini Lopes, 2024), suggesting that their welfare may not be negatively impacted by these specific wastes. Conversely, there is evidence suggesting that BSFL may not survive or grow well, and thus experience poorer welfare, on feeds high in indigestible fibre or low in nutrients (Beyers *et al.*, 2023). If these are used, mixing them with other feed sources can help address nutritional challenges, improving both production outcomes and welfare (Barrett *et al.*, 2023a).

Insects may also be reared at high stocking densities in production facilities (Yakti *et al.*, 2022). Some argue that high stocking densities are unlikely to harm insect welfare, citing their occurrence in dense populations in nature (Erens, 2012). However, the principle that 'naturalness' does not necessarily equate to good welfare applies in this case as well. Furthermore, it is unclear which stocking densities are typical in nature, making it difficult to determine whether current farm densities are too high even relative to this standard (Barrett *et al.*, 2023b). High stocking densities occur in many animal production systems, where there is often a tension between welfare and productivity goals (Rowe *et al.*, 2024). Research on acceptable stocking densities for insects will be crucial for understanding any welfare compromises in insect production facilities related to stocking density.

Many welfare challenges can be mitigated with a deeper scientific understanding of conditions that benefit or harm farmed animals. For instance, recent studies have shown that certain methods of insect slaughter, when executed according to well-defined standard operating procedures, can achieve 97-99% instantaneous (and thus humane) death for insects (Barrett *et al.*, 2024; Zacarias *et al.*, 2024). Importantly, insects have significant physiological and behavioural differences compared to commonly farmed vertebrates (Johnson and Barrett, 2024). Thus, while some tools or indicators from traditional animal welfare science will apply, the field of insect welfare science will need to be thoughtful in how it proceeds when using these tools or developing novel ones (Barrett and Fischer, 2024).

Ultimately, welfare science can provide empirical evidence to support higher welfare practices in insect farming, which may also offer economic benefits that encourage adoption by producers (Barrett and Adcock, 2023). While some improvements are already supported by existing research, more data specifically focused on insect welfare and affect – not just survival, growth, reproduction, or 'naturalness' – is needed. Such data will be crucial for developing strategies to assess welfare at scale on farms and for promoting collaboration between academia and industry. To ensure that research outcomes are applicable to industry needs, transparent collaboration among producers, veterinarians, welfare scientists, and other relevant experts in the fields of insect health and welfare is essential. In the long term, evidence-based and practice-sensitive welfare regulations may also yield economic benefits for the industry (Barrett and Adcock, 2023; Niyonsaba *et al.*, 2025).

9 Market realities facing circular insect-based businesses

Over the past decade, the insect industry has experienced exponential growth, accompanied by increasing expectations to provide sustainable and affordable solutions for food and feed production. As a result, the industry is under pressure to deliver innovations that could revolutionize the global agroecosystem. However, this rapid development has also led to criticisms on several fronts, including environmental, health and safety, and animal welfare concerns. While some of the criticisms are valid and merit further investigation – such as the ethical considerations surrounding industrial insect-rearing practices – others are overly simplistic, contradictory or misleading. For instance, the insect industry has been criticised for not being truly circular or as environmentally friendly as claimed. Yet at the same time, critics argue that the risks of rearing insects on waste substrates are too high. This criticism frequently overlooks the precautionary measures already in place to ensure safe progress toward greater circularity while safeguarding human health. In this article, we examine the latest scientific developments within the insect industry and explore potential pathways for the sector to fully realise its environmental, ethical, and economic potential.

Another aspect we have not addressed is the broader economic and industrial landscape in which the emerging insect production sector is attempting to establish itself. Many large-scale insect producers are encountering financial difficulties, with some filing for bankruptcy, or reporting economic distress.[1] These challenges could be interpreted as an indication of a fundamental limitation within the insect production industry. However, Hamam *et al.* (2024) examined the potential of the insect sector to contribute to a circular bioeconomy and identified high production costs and regulatory barriers as primary obstacles to the successful establishment of insect production systems. While this article has already discussed regulatory challenges, it is equally important to acknowledge the economic constraints which are, in part, a consequence of the novel circular production strategies that the industry seeks to implement.

Circular production systems face several structural limitations that hinder their competitiveness on a global scale. While scarcity has historically encouraged circular practices like reuse, waste tends to accumulate in times of excess (Morseletto, 2023). Circular bio-based industries face high costs, limited profitability, and competitive disadvantages, such as a lack of subsidies, compared to linear production models which externalise environmental harm rather than incorporating it into production expenses (Dace *et al.*, 2024; Neves and Marques, 2022). The apparent cost-efficiency of conventional products competing with insect protein, such as soy and fishmeal, partly stems from the fact that their current and future environmental impacts, such as deforestation, loss of biodiversity and overfishing, are not reflected in market prices (Searchinger *et al.*, 2019). In linear economic models, environmental degradation represents a hidden cost borne by ecosystems and society, rather than by producers (Buggle *et al.*, 2021).

1 See https://agfundernews.com/exclusive-aspire-food-group-cuts-staff-temporarily-scales-back-production-at-cricket-farm; https://www.feednavigator.com/Article/2025/02/25/ynsect-seeks-to-enter-a-judicial-recovery-procedure/; https://www.impactloop.se/artikel/kampat-i-atta-ar-med-att-mjolmaskar-ska-bli-mat---nu-gar-tebrito-i-konkurs; https://www.feednavigator.com/Article/2025/01/29/agronutris-placed-under-protection-by-french-commerical-court/; https://www.asahi.com/ajw/articles/15525984.

Key barriers to transitioning from a linear to a circular economy include low consumer awareness and lack of policy coherence. Unlike linear systems, circular transitions require systematic changes across the entire value chain, encompassing management, production, and consumer behaviour. Iacovidou *et al.* (2021) emphasised the need for a holistic approach that integrates political, technical, environmental and social considerations when transitioning from linearity to circularity. However, despite increasing recognition of circular economy principles, linear economy structures continue to dominate the global market. Notably, the proportion of secondary materials used in the global economy declined from 9.1% in 2018 to 7.2% in 2023, even as overall material consumption increased by 28% over the same period (CGR Global, 2024). Consequently, insect-based products currently exhibit higher upfront costs compared to conventionally produced alternatives such as soy and fishmeal (Biteau *et al.*, 2024). Ultimately, this raises the question: Is the challenge faced by the insect industry a failure of the sector itself, or rather a failure of the market to facilitate the transition to a circular economy, thereby preventing insect farmers from competing on an equal footing?

10 Conclusion

Effectively advancing the insect-based bioeconomy requires playing a delicate balancing act between ambitious sustainability goals and critical considerations of safety, environmental responsibility, economic feasibility, and ethical standards. Framing these challenges as catalysts for interdisciplinary innovation can drive the transition into circular agriculture, fostering improved welfare practices and the development of sustainable markets. To unlock the industry's full potential, stakeholders – including researchers, regulators, producers, and consumers – must continue to collaborate transparently, adapt to emerging knowledge, and collectively advocate policy frameworks that support a genuinely sustainable transition from linear to circular food systems.

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