The Environmental Performance of the Insect Industry: Data, Trends, and Context

A Life Cycle Assessment (LCA) Perspective – January 2026

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Index

About this Paper…………………………………………………………………………………………….Pg 03

Executive briefing……………………………………………………………………………………...Pg 04

I. Scientific foundations of insect bioconversion for sustainable food and feed systems………………………..Pg 06

II. Demonstration at Scale: The critical transition from pilot projects to commercial viability, now supported and validated by industry data from operational facilities………………………………………………………………Pg 14

III. Challenges & The Need for Harmonisation…………………………………………………………Pg 20

IV. Conclusions and Outlook………………………………………………………………………...Pg 22

V. Annex- Scientific Bibliography……………………………………………………………………...Pg.23

About this Paper

This document was prepared by IPIFF based on data provided by its member companies—which include the EU leading insect production firms—as well as input from its academic network, bringing together some of the world's most recognised universities and research centers in entomology.

In addition, to develop this document, IPIFF consulted highly renowned specialists in entomology and Life Cycle Assessment (LCA) development, including Professor Dr. Sergiy Smetana and Professor Dr. Seyyed Hassan.

Finally, this document is accompanied by seven third-party-assessed LCAs from IPIFF member companies, as well as a comprehensive scientific bibliography. Together, they help clarify the key contextual factors needed to accurately interpret the industry's rapidly improving environmental profile and its future potential.

Executive Briefing

Over the past two decades, insect protein has drawn growing scientific interest as a nutritious and sustainable alternative to conventional protein sources. Insects offer a compelling nutritional profile—rich in high-quality protein, essential amino acids, lipids, and micronutrients—with promising applications in both food and feed systems.

Beyond their nutritional value, insects align closely with the urgent needs of a more sustainable global food system. They require significantly less land and water than traditional livestock, produce substantially lower greenhouse gas emissions, and can be reared on organic side-streams and waste biomass—embodying the principles of a circular economy.

By reducing pressure on terrestrial and marine ecosystems, including overfished stocks and biodiversity-sensitive habitats, insects are positioned as a key component of more resilient food systems. This potential received formal recognition in 2013, when the Food and Agriculture Organization (FAO) of the United Nations published '*Edible Insects: Future Prospects for Food and Feed Security*—the first comprehensive global assessment of insects as a protein source'*.

In the years that followed, a wave of start-ups sought to translate this scientific promise into market and industrial reality, developing insect-based protein meals, lipids, and organic fertilizers across diverse species and production systems. As the sector emerged, demonstrating environmental performance became a central priority, and Life Cycle Assessment (LCA) established itself as the primary framework for evaluating the industry's environmental footprint—capturing impacts across the full production chain, from substrate sourcing to processing and co-products.

After a decade of industrialisation, the insect production sector now stands at a pivotal juncture. With industrial-scale facilities operating globally and multi-year operational data available, the industry is increasingly able to ground LCA discussions in real production performance rather than lab-scale data.

Nevertheless, as with most agro-industrial sectors, establishing a single LCA that represents the insect industry as a whole remains inherently challenging. Environmental outcomes can vary considerably depending on factors such as insect species, production technologies, feedstock, energy sources, and scale.

This document is organized into three sections:

1. The first section revisits the scientific rationale driving the growing interest in insect-derived nutrients and explores the potential role of insects in future food and feed systems.
2. The second provides an up-to-date assessment of environmental performance across different production models, based on multi-year operational data from industrial-scale facilities.
3. The third examines key methodological considerations for developing a more consistent industry-wide life cycle assessment (LCA) framework and outlines the essential steps to enhance comparability and transparency across the sector.

I. Scientific foundations of insect bioconversion for sustainable food and feed systems

Ensuring the long-term sustainability of global food systems has emerged as one of the defining challenges of the XXI century. Food production is a major driver of environmental pressures worldwide, contributing significantly to greenhouse gas emissions, land-use change, biodiversity loss, freshwater depletion, and nutrient pollution. As global demand for food—particularly animal-derived protein—continues to rise, improving the environmental performance of food production systems has become a key priority for both scientific research and public policy.

In this context, Life Cycle Assessment (LCA) has become one of the most widely used tools for evaluating the environmental impacts of food production. It enables systematic comparisons across different production systems and helps identify opportunities for improvement.

Insect-based production systems have attracted increasing attention as a potentially more sustainable route for producing nutrients for food and feed. Early LCA studies suggested that insects could offer significant environmental advantages over conventional livestock production, particularly in terms of greenhouse gas emissions, land use, acidification, and resource efficiency **(Table 1)**.

Table 1: Comparison of some life cycle assessment (LCA) impact categories between main reared insects and other conventional protein sources (GWP: global warming potential; AC: acidification; ALOP: agricultural land occupation; LU: land use; FFE: fossil fuel depletion).

	Species	GWP [*kg* CO_2-eq]	AC [*g* SO_2-eq]	ALOP [m^2]	LU [m^2]	FFE [*MJ*-eq]	Reference
1 kg of Mealworm edible mass	*Tenebrio molitor larvae*	2.8	21.88	3.07	–	29.36	Dreyer et al. (2021)
1 kg of Black Soldier Fly Larva meal	*Hermetia illucens larvae*	1.16	5.3	–	0.48	17.9	Smetana et al. (2019)
1 kg of Cricket edible protein	*Gryllus bimaculatus* and *Acheta domesticus*	1.55–2.57	0.05–0.08 (mol H^+ eq)	–	–	–	Halloran et al. (2017)
1 kg of beef meat		33.3–99.5	318.8–343.6	–	43.2–326.2	–	Harwatt et al. (2024)
1 kg of pork meat		12.3	142.7	–	17.4	–	Harwatt et al. (2024)
1 kg of broiler edible meat		4.5	98.37	12.5	–	43.96	Dreyer et al. (2021)

1 kg of soybean protein meal		**4.09**	**17.61**	**–**	**4.34**	**31.17**	**Thévenot et al. (2018**

The environmental advantages identified in early life cycle assessment (LCA) studies stem from several distinctive features of insect bioconversion systems.

The following sections examine these key characteristics—including efficient resource use, high nutritional value, integration with circular economy models, valorisation of co-products, and broader system-level benefits—and explore how they collectively contribute to the sustainability potential of insect-based production.

I.1. Efficiency resource use and nutritional value

Insects combine high nutritional value with remarkable feed conversion efficiency, making them a compelling alternative protein source.

Many species contain over 50% protein (dry weight) and provide all essential amino acids. They also contain beneficial lipids, including unsaturated fatty acids and medium-chain fatty acids such as lauric acid, along with important micronutrients such as iron and zinc.

Table 2: Average nutritional values of some of the most diffused, consumed or commercially available worldwide edible insects and of meat expressed per 100 g of edible portion (Rumpold and Schlüter, 2013; Meyer-Rochow et al., 2021; Orkusz, 2021; Zhou et al., 2022).

Common name	Species	Protein [g]	Fat [g]	Fiber [g]	Cholesterol [mg]
House cricket (Adults)	***Acheta domesticus***	**62.6–70**	**12.2–22.8**	**8–22**	**98.5**
Field cricket (Adults)	***Gryllus bimaculatus***	**58.3**	**11.9**	**9.5**	**195**
Migratory Locust	***Locusta migratoria***	**48.7–61.3**	**13.4–38.1**	**8.8–9.6**	**–**

Mealworm (Larvae)	***Tenebrio molitor***	**47.2–57.1**	**32.4–43.1**	**5–14.9**	**51.3**
Superworm (Larvae)	***Zophobas morio***	**43.1–46.8**	**35–42**	**6–13**	**45**
Mopane worm	***Gonimbrasia belina***	**35.2**	**15.2**	**–**	**–**
Black Soldier Fly (Larvae)	***Hermetia illucens***	**34.9–39**	**27.93–32.6**	**7.5–12.4**	**–**
Silkworm (Larvae)	***Bombyx mori***	**53.7–69.8**	**8–9.5**	**5.9–6.3**	**–**
Wax moth (Larvae)	***Galleria mellonella***	**34–41.2**	**51.4–58**	**8.9–12.1**	**75.3**
Pork shoulder	***Sus scrofa domesticus***	**16.89**	**7.05**	**–**	**50.02**
Beef sirloin	***Bos taurus***	**20.1**	**3.5**	**–**	**59**
Chicken breast	***Gallus domesticus***	**21.5**	**1.3**	**–**	**58**

Nutritional comparisons require careful interpretation. Factors such as protein digestibility, mineral bioavailability, and the presence of structural components like chitin can influence the actual nutritional value available to humans or animals.

The data in **Table 2** should therefore be viewed as an overview of the nutritional potential of different insect species rather than a direct equivalence with conventional foods. Nevertheless, the broader picture highlights insects’ strong potential as nutrient-dense ingredients for both food and feed applications.

At the same time, insects convert feed into body mass far more efficiently than conventional livestock (**Table 3**). This efficiency reduces the land, water, and energy required per unit of protein, directly contributing to the favorable environmental outcomes reported in life cycle assessments.

Table 3. Average feed conversion ratios observed in insect species compared to conventional livestock, (Lalander, 2019; Bosch, 2019; Halloran, 2016, 2020; Smetana, 2019)

Species / System	Feed Conversion Ratio (kg feed : kg body mass)
Black Soldier Fly (Hermetia illucens)	**1.4–2.6**
House Cricket (Acheta domesticus & related)	**2.3–6.1**
Mealworm (Tenebrio molitor)	**3.8–19.1**
Beef cattle	**~8.8**
Pork (swine)	**~4.0**
Broiler chicken	**~2.3**

Taken together, nutrient density and biological efficiency explain why insects are both a high-quality and environmentally efficient protein source, supporting their role in sustainable food and feed systems.

I.2. Circular economy integration

On top of their high bioconversion efficiencies, a key advantage of insect production lies in the ability of certain species—such as the Black Soldier Fly larva—to transform low-value organic streams into multiple high-value outputs. These include nutrient-rich protein for food and feed, as well as frass, a concentrated organic fertilizer that can replace synthetic alternatives while reducing waste management burdens.

Life Cycle Assessment (LCA) of insect farming is greatly enhanced when it accounts for the valorisation of insect frass as a high-quality organic fertilizer. Unlike traditional manures, insect frass often features a more concentrated and balanced nutrient profile, with an NPK ratio in the range of 3–2–2—comparable to or even richer than poultry manure, and substantially more concentrated than cattle or pig manure.

This valorization yields a dual environmental benefit: it avoids the waste management burdens associated with the frass itself, and more importantly, it generates a favorable credit in the insect farming system's overall environmental balance by displacing the production of energy-intensive synthetic fertilizers.

This capability enables the development of circular models that rely on undervalued agri-food by-products or waste streams, directly contributing to the circular bioeconomy—a central pillar of Europe's sustainability strategy.

By using agri-food waste and by-products as substrates for large-scale rearing, insects offer a potential solution to two pressing challenges: the growing volume of organic waste and by-products, which generate disposal costs and environmental pollution, and the rising global demand for protein for both food and feed (Salomone, 2017). Insect bioconversion mirrors natural ecological processes—in ecosystems, insects, worms, fungi, and bacteria decompose organic matter and recycle nutrients. Under controlled conditions, certain insect species can intensify this natural behavior, making it viable for sustainable, bio-circular economy systems (Ortiz, 2016; Fowles and Nansen, 2020).

Scientific interest in insect bioconversion has increased dramatically: a search of the keywords "insect bioconversion" or "insect waste valorisation" on Science Direct reveals a 530% rise in publications between 2019 and 2022, reflecting growing recognition of its potential (Van Huis, 2013; Madau, 2020).

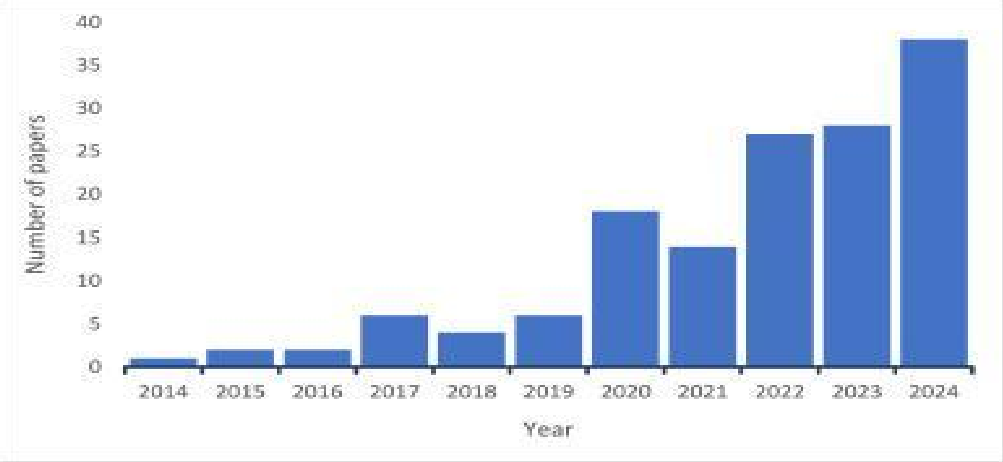


Fig. 1. Distribution of research papers published in Science Direct containing the keywords “insect bioconversion” or “insect waste valorisation” within Title, Abstract and Keyword fields, by year (https://www.sciencedirect.com/, accessed: October 2024).

The viability of this model depends heavily on regional and local contexts, particularly the availability of side-streams, which may already be used for purposes such as animal feed or biogas production. To truly assess the value of insect bioconversion, one must consider the entire value chain: redirecting waste streams that are already going to animal farming and then feeding the resulting insects back to the same animals offers little added benefit. Genuine opportunities arise when insect bioconversion is used to further upcycle side-streams, thereby improving both efficiency and sustainability.

For example, using European crop side-streams as feedstock for insects to produce protein-rich nutrients for aquaculture diversifies the protein sources typically provided by fishmeal or soy-based meal. This approach strengthens Europe’s self-sufficiency in a system that currently depends heavily on imported feed ingredients. Similarly, nutrients from side-streams normally destined for biogas can first be recovered by insects for use as feed, with the residual frass then directed to biogas production. This creates multiple layers of benefit, closes nutrient loops, and delivers systemic environmental advantages.

By strategically integrating insects into such processes, regions can optimize resource use, enhance circularity, and unlock new environmental and economic value—demonstrating that insect-based systems are a highly promising tool for advancing Europe’s circular bioeconomy.

I.3. Broader system-level benefits

Standard LCAs often fail to capture critical systemic environmental benefits and avoided burdens. For example, reducing reliance on conventional livestock feed crops such as soy can help limit deforestation and associated greenhouse gas emissions. Likewise, providing a nutrient-dense alternative to fishmeal may reduce pressure on overfished stocks while avoiding seabed disruption and nutrient release caused by industrial fishing. Additionally, upcycling organic waste through energy-dense valorization systems can further reduce overall carbon emissions and help close nutrient loops.

To fully account for these avoided emissions, a consequential LCA is required, as it captures the broader system-level consequences of production decisions. This stands in contrast to conventional attributional or allocation-based LCA, which focuses on direct production impacts and does not reflect such indirect benefits. As LCA methodologies evolve, integrating consequential approaches will enable a more complete assessment of the environmental performance of insect-based systems, providing a robust foundation for decision-making and policy development.

II. Demonstration at Scale: The critical transition from pilot projects to commercial viability, now supported and validated by industry data from operational facilities.

Over the past 15 years, a new wave of startups has transformed the promise of insect-based proteins into a commercial reality. Building on early academic research that positioned insects as a sustainable alternative for food and feed, these companies have focused on developing viable industrial-scale models.

Europe has led this movement, attracting over €2 billion in investment. This funding has driven advances in rearing and processing technologies, as well as the construction of large-scale production facilities. These industrial efforts have been critical for testing diverse approaches and validating—under real-world conditions—the technical feasibility, economic competitiveness, and environmental performance of insect production.

Now that players have reached industrial scale, we can, for the first time, draw on Life Cycle Assessments (LCAs) based on actual operational data.

These studies rely on multi-year production records from full-scale facilities, offering a far more accurate picture than earlier assessments that used laboratory or pilot data—which often depended on secondary estimates from small-scale facilities with limited optimization of feedstocks, energy use, or rearing environments (e.g. DEFRA study). Importantly, these new LCAs confirm the strong environmental performance of insect-based ingredients, frequently showing results that improve upon initial estimates.

Below are figures collected from third-party reviewed LCAs from major insect producers in Europe at various stages of scale-up.

Table 4: Summarises the latest available product-level LCA data from leading European insect producers, compared to common benchmarks. All data is presented as kg of CO_2 equivalent per kg of product (kg CO_2eq/kg) using c European Commission's Product Environmental Footprint (EF) methodology.

Protein meal						
Company	*Method*	*Products*	*Year*	kg CO2/Kg Product	Scale stage	Species
Innovafeed	EF 3.0	Protein meal	2025	1.2	Commercial	*Hermetia Illucens*
Protix	EF 3.1	Protein meal	2023	1.1	Commercial	*Hermetia Illucens*
Tebrio	EF 3.1	Protein meal	2023	1.8	Industrial Demonstration	*Tenebrio molitor*
Nasekomo	EF 3.1	Protein meal	2024	8.2	Industrial Demonstration	*Hermetia Illucens*
Invers	EF 3.1	Protein meal (full fat)	2024	0.82	Commercial	*Tenebrio molitor*
Norinsect	*	Protein meal	2025	0.59	Industrial Demonstration	*Tenebrio molitor*
Conventional ingredients	EF 3.1	Soybean protein concentrate, EU	2022	5.8		
	EF 3.1	Blue whiting fish meal, Norway	2021	2.1		
	EF 3.1	Fish meal anchovy, Peru	2022	0.6		
	EF 3.1	Poultry PAP, EU	2021	1.0		

Lipids						
Company	*Method*	*Products*	*Year*	kg CO2/Kg product	Scale stage	Species
Innovafeed	EF 3.0	Lipids	2025	0.5	Commercial	*Hermetia Illucens*
Protix	EF 3.1	Lipids	2023	0.6	Commercial	*Hermetia Illucens*
Tebrio	EF 3.1	Lipids	2023	0.3	Industrial Demonstration	*Tenebrio molitor*
Nasekomo	EF 3.1	Lipids	2024	1.89	Industrial Demonstration	*Hermetia Illucens*
NorInsect	*	Lipids		0.62	Industrial Demonstration	*Tenebrio molitor*
Conventional ingredients	EF 3.1	Crude soybean oil, EU	2022	3.9		
	EF 3.1	Crude palm kernel oil, Malaysia	2022	5.2		
	EF 3.1	Crude coconut oil, Global	2022	6.5		

Note: *Norinsect analysis follows leading PEF/PEFCR Feed methodologies, using Ecoinvent data and IPCC models, consistent with GFLI guidelines*

This data illustrate a number of elements to be considered when looking at industry level data:

A. No single LCA: impact depends on production models

Insect production operates as a complex and evolving biological system, with environmental performance varying significantly based on several key factors: insect species, feedstock and energy sources, level of technological integration, scale, and evaluation methods (e.g., mass allocation vs. economic allocation).

This variability is not unique to insects—it is inherent to all agricultural industries, where environmental outcomes differ widely depending on how and where production occurs. Within the insect sector, this range of outcomes reflects an industry still in the process of optimising and innovating. Nevertheless, overall results consistently confirm the environmental benefits of insect production systems when compared to conventional benchmarks in similar applications.

B. Primary industrial scale data confirm environmental benefits of insect production systems

These new LCAs—some based on multi-year production records from full-scale facilities—confirm and often improve upon the strong environmental performance initially theorized for insect-based ingredients. This progress is driven by several key factors:

- ☐ **Feedstock optimisation:** Commercial-scale operations increasingly integrate optimised sourcing and refined rearing protocols into their industrial design, whether by selecting superior feedstocks or improving rearing conditions that lead to better conversion ratios.
- ☐ **Energy and utility optimisation**: Whereas lab-scale estimates often rely on non-optimised rearing conditions and primary energy and utility streams, industrial players have been optimising energy use through improved processes, HVAC design, and sourcing strategies. They leverage

secondary energy (e.g., Innovafeed's use of waste heat from a neighboring biomass boiler) and utility streams (e.g., closed-loop water recycling systems)—factors not considered in earlier studies that dramatically reduce emissions.

☐ **Waste valorisation:** Further valorisation of by-products, such as frass, continues to improve the overall environmental profile.

☐ **Technology integration and process automation:** As operators move from pilot to commercial-scale operations, the benefits of scale and automation become substantial, as demonstrated by the figures in the next section.

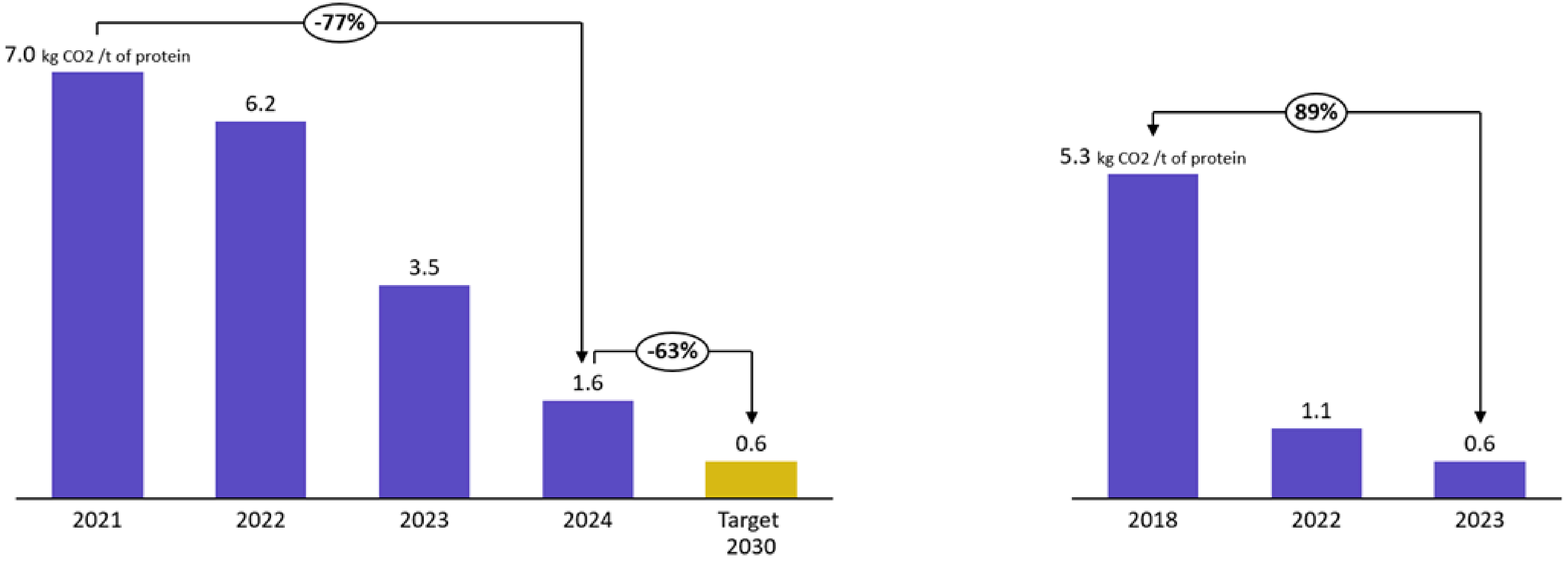
C. Further reductions still coming via continuous improvement through scale-up and process optimization

The emerging industry is still in the early stages of its industrial scale-up, yet it is already achieving rapid and measurable improvements in environmental performance. These gains are driven by the expansion of production facilities and ongoing process optimisation.

As companies scale up, they have accomplished higher production yields, improved bioconversion efficiency, reduced energy consumption, and better waste management—while feedstock remains the primary source of emissions. This trend is evident when comparing data from players in the pilot phase to those in the commercial phase, or by tracking individual companies throughout their scale-up journeys.

Over the past three years, significant progress has been made by Innovafeed and Protix, which currently operate Europe’s largest factories (see **Figure 2**). Their advancements provide confidence that the industry will continue to meet ambitious life cycle assessment (LCA) targets as industrialization and innovation move forward.

Fig. 2: Recent trends in CO_2 emissions (kg CO_2 / ton of protein meal) from two major EU producers. Reductions are driven by volume ramp-up at factories and continuous process optimisation.



INNOVAFEED
Methodology: EF 3.0

PROTIX
Methodology: Impact 2002+

Beyond reducing carbon emissions, the scale effect also drives improvements in other critical environmental impact areas—such as land use and water consumption. Larger capacities and vertical integration can minimise land occupation, while enhancing closed-loop systems and synergies with feedstock suppliers (e.g., valorising wet side streams that would otherwise require treatment) can reduce water use.

These findings are drawn from a recent study published in the Journal of Cleaner Production (Francis, Schmitt, & Smetana, 2025), which provides a direct comparison of the environmental performance of a leading producer (Protix) between its 2019 pilot-scale operations and its 2023 large-scale industrial system. The results demonstrate dramatic, quantifiable reductions across all key environmental impact categories per kilogram of product.

D. Environmental benefits depend on application and benchmark

Benchmarking should take into account the specific ingredient being replaced. Compared to conventional options such as fishmeal or soy protein concentrate, insect-derived products stand out for their potential to reduce CO_2 emissions, lessen biodiversity loss, and lower land use impacts.

As food and feed production expands to meet global demand, new sources of nutrients are often produced through less sustainable methods. Expanding soy output, for instance, typically drives deforestation. As a result, each additional unit of ingredient produced tends to carry a higher environmental cost—soy yield optimisation has largely plateaued, making deforestation necessary to boost production. As part of a new generation of sustainable ingredients, insect-based products offer a key solution for closing the ingredient gap and decarbonising supply chains.

We believe the fairest benchmark consists of food and feed sources that are coming to meet new demand, since insect products are also emerging nutrient sources striving to fulfill that same demand.

This peer-reviewed evidence shifts the discussion from theoretical potential to verified performance, confirming that industrialisation is the primary driver of environmental efficiency.

III. Challenges & The Need for Harmonisation

The presentation of a single, static "Insect LCA" figure would be a misrepresentation of a complex and dynamic biological industry. Instead of a weakness, the inherent diversity in environmental performance is a hallmark of a vibrant, innovative sector undergoing rapid optimisation. Impact variation is driven by several key factors, including species (e.g., the temperate *Tenebrio molitor* vs. the tropical *Hermetia illucens*), production model (vertical farming vs. horizontal trays), production volume (pilot vs. commercial scale), feedstock composition, and technology integration (e.g., renewable energy, industrial symbiosis).

Crucially, this variation is not unique to insect farming; it is a well-documented characteristic of all agricultural sectors. A landmark meta-analysis by Poore and Nemecek (2018) quantified the substantial intra-product variability within conventional systems, showing, for example, that the carbon footprint of a serving of red meat can vary by a factor of 50 depending on production methods. While establishing a clear hierarchy of impacts across food categories, this research fundamentally demonstrates that variation is the rule, not the exception, in biological production.

For a nascent industry like insect farming, this inherent variability is compounded by a steep learning curve, where rapid temporal improvements are expected as systems mature. The diversity we see today is therefore not a sign of confusion, but a map of the many pathways being pioneered towards optimal sustainability.

A significant source of perceived "variation" in published results stems not from the industry itself, but from the choice of LCA methodology. The field distinguishes between two primary approaches, each answering a fundamentally different question:

Attributional LCA (ALCA): This approach provides a static "snapshot" of the environmental flows associated with a product's life cycle at a specific point in time. It answers the question: "What is the share of global environmental burden attributable to this product?" Using average data and standardised allocation rules (e.g., for co-products), ALCA is the method of choice for applications like Environmental Product Declarations (EPDs), carbon footprinting, and hotspot identification. The vast majority of current insect LCAs are attributional.

Consequential LCA (CLCA): This approach is change-oriented and dynamic. It aims to model the environmental consequences of a specific decision, answering the question: "What are the total environmental impacts that will result from a change in demand for this product?" Instead of average data, CLCA models the marginal suppliers—the producers who will actually ramp up or down in response to a market shift. It uses system expansion to account for displaced or induced production in other markets.

For an emerging sector positioned as a solution to sustainability challenges, the distinction is paramount. An ALCA of insect meal describes the footprint of a specific ton produced today using a given waste stream. A CLCA, however, asks the more systemic question: "If we scale up insect farming to replace 10% of European soy imports, what happens?" It would model the displacement of the marginal soy supplier—typically linked to land-use change on the deforestation frontier in South America—revealing an avoided impact far greater than the average soy footprint suggests. The field is increasingly recognising that to understand the insect sector's true role in a food system transition, a shift towards consequential thinking is essential.

This leads to a critical point for fair comparison: the environmental benefit of an insect ingredient is intrinsically linked to what it displaces. Insect products are new sources of high-quality nutrients entering the market to meet growing global demand. They are not merely substituting a static, average unit of an existing commodity.

Therefore, the most relevant benchmark is the marginal production of conventional ingredients—the next unit that would be produced to meet demand. This marginal unit is almost invariably associated with a higher environmental cost than the historical average, representing, for example, soy from newly deforested land in the Cerrado or fishmeal from increasingly stressed and overexploited fisheries. By offering a pathway to meet new demand without triggering deforestation, biodiversity loss, or overfishing, insect-based ingredients provide a systemic benefit that a simple, average-to-average ALCA comparison may fail to capture.

IV. Conclusion and Outlook

Data gathered this past three years from players with different scale-up models of insect production systems confirm that the industrialised European insect sector is not merely a promising concept, but is a low-carbon solution already delivering on its environmental promise. The data demonstrates a clear and rapid trajectory of improvement, driven by the transition from pilot-scale estimates to verified commercial performance.

As the industry continues its ascent up the learning curve—through advancements in genetics, automation, processing efficiency, and deeper integration into circular bio-economies—its environmental advantage tends to solidify. Insect-derived ingredients represent far more than an incremental improvement. They signify a systemic shift towards a more resilient, circular, and sustainable food system.

For lawmakers, this means creating regulatory frameworks that recognise the full consequential benefits of the sector. For value-chain partners, it offers a verifiable pathway to decarbonise supply chains. For investors, it signals a robust and improving asset class with clear environmental credentials. For policy makers, supporting growth and development of insect production systems represent a unique opportunity to build a sustainable and decarbonised industry, bringing circularity, resilience and sovereignty to key challenges of food security and sustainability for our societies.

Annex- Scientific Bibliography

1.Other references for Foundational LCA and comparative studies

1. **Francesco Iannielli, Antonio Dolce, Federica De Stefano, Jesus D. Fernandez-Bayo, Carmen Scieuz, Patrizia Falabella (2025).** Transformative potential of insect bioconversion and its role in circular economy. *Journal of Environmental Management*, Volume *396, 128091*
   - **Key highlights:** The study by Iannielli et al. (2025), published in the Journal of Environmental Management, positions insect rearing as a strategic tool for sustainable development by synthesizing key insights into its role within a circular economy framework, where insects are highlighted for their efficient bioconversion of organic waste into high-quality products for food, feed, and other valuable compounds. The review emphasizes that while Life Cycle Assessment (LCA) is critical for evaluating the true environmental impact of these operations, the primary future challenge lies in scaling up production, particularly through the automation of Black Soldier Fly larvae rearing to achieve economic viability. Ultimately, by integrating environmental management principles with technological advances and navigating the evolving global legislative landscape, the study concludes that insect bioconversion holds transformative potential to support more circular and resource-efficient agri-food systems.
2. **Anna Vatsanidou, Styliani Konstantinidi, Eleftherios Bonos, Ioannis Skoufo (2025):** Comparative Life Cycle Assessment of Animal Feed Formulations Containing Conventional and Insect-Based Protein Sources. AgriEngineering, Volume 7, Issue 9, 10.3390/agriengineering7090275.
   - **Key highlights:** The study indicates that replacing soybean meal with insect meal *(Tenebrio molitor)* in pig feed significantly reduces environmental impacts, primarily because crop-derived ingredients—especially soy—drive most burdens through land use change and fertilizer inputs. Insect meal demonstrated advantages in scalability, land efficiency, and waste valorization potential. The study also noted that fishmeal carries critical sustainability concerns beyond LCA scope, such as overfishing, and concluded that a protein-based
3. **Aditya Francis, Eric Schmitt, Sergiy Smetana (2025):** Making better Bugs: Improving black soldier fly production for a more sustainable future
   - **Key highlights:** Industrial scale model of insect production and Life Cycle Assessment.
4. **Vinci G, Prencipe SA, Masiello L, Zaki MG (2022).** The application of Life Cycle Assessment to evaluate the environmental impacts of edible insects as a protein source. *Earth* 3(3):925-938.
   - **Key highlights:** Reviews LCA studies across insect species and functional units, concluding that insects typically outperform conventional animal protein in climate and land-use indicators when waste or by-products are used as feed inputs.
5. **Iburg M (2022).** Comparative Life Cycle Assessment of insect and soybean-based protein for the European market. *Sustainability* 14(20):13486.
   - **Key highlights:** Shows that insect protein can be competitive with imported soy protein in several key impact categories, especially climate change and land use, when realistic European production conditions and co-product handling are considered.

6. **Halloran A, Roos N, Eilenberg J, Cerutti A, Bruun S (2020).** Life cycle assessment of edible insects for food protein: a review. *Int. J. Life Cycle Assess.* 25:1300–1318.
    - **Key highlights:** Confirms that most LCAs of edible insects report substantial reductions in GHG emissions, land use and in some cases energy demand compared with beef and often with pork and poultry, while also clarifying methodological needs for policy-relevant LCAs.
7. **Smetana S, Schmitt E, Mathys A (2019).** Sustainable use of *Hermetia illucens* insect biomass for feed and food: attributional and consequential life cycle assessment. *Resour. Conserv. Recycl.* 144:285–296.
    - **Key highlights:** Attributional LCA shows insect protein comparable to or better than several conventional proteins; consequential LCA demonstrates that using otherwise non-utilised food-industry side-streams can substantially reduce overall system impacts and support circular-economy objectives.
8. **Halloran A, Roos N, Eilenberg J, Cerutti A, Bruun S (2016).** Life cycle assessment of edible insects for food protein: a review. *Agron. Sustain. Dev.* 36(4):57.
    - **Key highlights:** Synthesises early LCA work on insects and shows that, per unit protein, insects can have lower greenhouse gas emissions and land use than conventional livestock when reared efficiently on low-value substrates.

2. Black soldier fly (Hermetia illucens) – LCA, waste valorisation and circularity

9. **Güldemund A, Klüber P, Weyand S, Zeller V (2025).** Integrating regional survey data into life cycle assessment: Prospective environmental consequences of directing apple pomace to insect farming. *Int. J. Life Cycle Assess.* 30:1666–1690.
    - **Key highlights:** Shows that diverting regional by-products (apple pomace) to BSF farming can reduce environmental burdens compared with current management options, supporting regional circular-bioeconomy strategies.
10. **Beyers M, Coudron C, Ravia R, Meers E, Bruun S (2023).** Black soldier fly larvae as an alternative feed source and agro-waste disposal route - a life cycle perspective. *Resour. Conserv. Recycl.* 192:106917.
    - **Key highlights:** Shows that using BSF larvae to valorise agricultural residues can improve overall system efficiency and reduce impacts of both waste management and feed production, especially when frass is recycled as a soil amendment.
11. **Ramzy RR, Goenka V, El-Dakar MA, Lee JSH (2023).** Assessing the environmental impacts of the black soldier fly-based circular economy and decentralized system in Singapore: a case study. *Sustainability* 17(13):6115.
    - **Key highlights:** Case-study evidence that decentralised BSF systems integrated into urban food chains reduce waste-management impacts and produce low-impact feed ingredients, aligning with urban circular-economy strategies.

12. **Ites S, et al. (2020).** Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. *J. Clean. Prod.* 248:119248.
    - **Key highlights:** Highlights that modular, scalable BSF facilities can enhance logistical efficiency, reduce transport-related impacts and tailor waste-valorisation solutions locally, thereby improving the environmental performance of food-waste management.
13. **Lalander C, et al. (2019).** Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). *J. Clean. Prod.* 208:211–219.
    - **Key highlights:** Shows that appropriate selection of organic waste feedstocks improves both larval yield and waste-reduction efficiency, reinforcing the role of BSF in high-efficiency organic waste treatment with co-production of feed.
14. **Bosch G, et al. (2019).** Conversion of organic resources by black soldier fly larvae: legislation, efficiency and environmental impact. *J. Clean. Prod.* 222:355–363.
    - **Key highlights:** Integrates technical and legislative aspects, concluding that BSF systems can efficiently convert diverse organic resources into feed while offering environmental benefits, provided regulatory frameworks allow safe use of suitable side-streams.
15. **Salomone R, (2017).** Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using *Hermetia illucens*. *J. Clean. Prod.* 140:890–905.
    - **Key highlights:** Demonstrates that BSF-based bioconversion of food waste can significantly reduce environmental burdens compared with conventional waste management routes, while generating valuable feed ingredients and reducing reliance on landfilling or incineration.

3. Mealworm (Tenebrio molitor) – LCA, water footprint and production efficiency

16. **Kotsou K, Chatzimitakos T, Athanasiadis V, Bozinou E, Lalas SI (2024).** Exploiting agri-food waste as feed for *Tenebrio molitor* larvae rearing: a review. *Foods* 13(7):1027.
    - **Key highlights:** Summarises evidence that mealworms can be reared on a variety of agri-food by-products, enhancing resource efficiency and reducing the environmental footprint of both waste management and protein production
17. **Dreyer M, Hörtenhuber S, Zollitsch W, Jäger H, Schaden L-M, Gronauer A, Kral I (2021).** Environmental life cycle assessment of yellow mealworm (*Tenebrio molitor*) production for human consumption in Austria – a comparison of mealworm and broiler as protein source. *Int. J. Life Cycle Assess.* 26:2010–2029.
    - **Key highlights:** Country-specific LCA showing that mealworms can achieve lower climate and land-use impacts per unit edible protein than broiler meat under realistic European production conditions.

18. **Thévenot, A., Rivera, J. L., Wilfart, A., Maillard, F., Hassouna, M., Senga-Kiesse, T., Le Féon, S., & Aubin, J. (2018).** Mealworm meal for animal feed: Environmental assessment and sensitivity analysis to guide future prospects. *Journal of Cleaner Production, 170*(1), 1260–1267.*
    - **Key insights:** It represents one of the first environmental impact assessments of mealworm meal specifically intended for animal feed. It uses Life Cycle Assessment (LCA) from "cradle to mill gate," meaning it evaluates the environmental impact from the production of raw materials all the way to the finished meal product.
19. **Miglietta PP, et al. (2015).** Mealworms for food: A water footprint perspective. *Water* 7(11):6190–6203.
    - **Key highlights:** Demonstrates that the water footprint of mealworm production is substantially lower than that of beef and often lower than other conventional meats, strengthening the case for insects in water-constrained contexts.
20. **Oonincx DGAB, de Boer IJM (2012).** Environmental impact of the production of mealworms as a protein source for humans – a life cycle assessment. *PLoS One* 7(12):e51145.
    - **Key highlights:** One of the first LCAs on insects for food; reports considerably lower GHG emissions, land use and fossil energy use per kg of protein for mealworms compared with traditional livestock such as beef, with similar or better performance than chicken and pork.

4. Other species and waste-conversion LCAs

21. **Halloran, A., Hanboonsong, Y., Roos, N., & Bruun, S. (2017).** Life cycle assessment of cricket farming in north-eastern Thailand. *Journal of Cleaner Production, 156, 83–94.*
    - **Key highlights:** The study examines a life cycle assessment comparing cricket and broiler farms in north-eastern Thailand. It founds that broiler production has greater environmental impacts than current cricket farming, with feed ingredients being the primary contributor to impacts in both systems, while a scaled-up cricket scenario offers opportunities for targeted improvements.
22. **van Zanten HHE, et al. (2015).** From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. *J. Clean. Prod.* 102:362–369.
    - **Key highlights:** Shows that housefly larvae can upcycle manure and other low-value substrates into feed ingredients with lower overall system impacts, turning a pollution source into a resource and reducing pressure on conventional feed crops.

5. Frass, soil health and nutrient cycling

23. **Wilson DD, Ray RL, Lohakare J (2025).** Black soldiers fly *Hermetia illucens* applications in circular economy and agricultural sustainability: a review. *Discov. Sustain.* 6:1347.
    - **Key highlights:** Integrates evidence on BSF larvae and frass, concluding that BSF systems support circular nutrient flows, reduce waste, and can enhance soil health and crop productivity when frass is applied appropriately.

24. **Helen C S Amorim, Amanda J Ashworth, Komala Arsi, M Guadalupe Rojas , Juan A Morales-Ramos, Annie Donoghue, Kelsy Robinson (2024).** Insect frass composition and potential use as an organic fertilizer in circular economies. *Journal of Economic Entomology, Volume 117, Issue 4, August 2024, Pages 1261-1268.*
    - **Key highlights:** The research shows that different insect species frass has a high organic matter content (73-77%) and a favorable N-P-K ratio (approximately 2.8-2.9% N, 1.1-1.5% P, and 1.8-2.2% K), with its precise nutrient composition—including higher levels of sulfur, copper, and iron—directly influenced by the larvae's rearing substrate.
25. **Ashworth, A.J., Amorim, H.C.S., Drescher, G.L (2024).** Insect frass fertilizer as soil amendment for improved forage and soil health in circular systems. *Sci Rep 15, 3024.*
    - **Key highlights:** The study investigated the agronomic potential of yellow mealworm (*Tenebrio molitor)* frass as a soil amendment in a two-year field study on bermudagrass forage production.
26. **Hellen Elissen, Rommie van der Weide, Luuk Gollenbeek (2023).** Effects of black soldier fly frass on plant and soil characteristics: a literature overview. *Report / Wageningen Plant Research No.WPR-996.*
    - **Key highlights:** The study assesses that Black soldier fly frass composition varies greatly depending on the larval diet, but on average it resembles common livestock manures in nutrient content, while having a higher organic matter content than compost or manure. Food-system, diet-level and policy-relevant context.
27. **Smetana S, Bhatia A, Batta U, Mouhrim N, Tonda A (2023).** Environmental impact potential of insect production chains for food and feed in Europe. *Anim. Front.* 13(4):112–120.
    - **Key highlights:** Synthesises European LCA data and concludes that properly designed insect value chains can reduce environmental impacts relative to conventional protein sources, especially when integrated with side-stream valorisation and efficient energy use.
28. **Gebremikael MT, van Wickeren N, Hosseini PS, De Neve S (2022).** The impacts of black soldier fly frass on nitrogen availability, microbial activities, carbon sequestration, and plant growth. *Front. Sustain. Food Syst.* 6:795950.
    - **Key highlights:** Demonstrates that BSF frass can improve soil nutrient availability, stimulate beneficial microbial activity and contribute to carbon sequestration, providing additional environmental benefits beyond protein production.
29. **Parodi A, et al. (2018).** The potential of future foods for sustainable and healthy diets. *Nat. Sustain.* 1(12):782–789.
    - **Key highlights:** Identifies insects among a set of “future foods” with high potential to improve the environmental performance of diets (GHG, land, water) while also contributing to nutritional adequacy when included in diversified, sustainable dietary patterns.
30. **Sánchez-Muros MJ, Barroso FG, Manzano-Agugliaro F (2014).** Insect meal as renewable source of food for animal feeding: a review. *J. Clean. Prod.* 65:16–27.
    - **Key highlights:** Positions insect meal as a renewable feed ingredient that can partially replace fishmeal and soy, potentially reducing land use change, overfishing and associated environmental impacts in livestock and aquaculture systems.

7. References (broader production and sustainability)

31. **Caparros Megido R, Jordan H, Miranda C, Katz E, et al. (2024).** A worldwide overview of the status and prospects of edible insect production. *Entomol. Gen.* (early view).
    - **Key highlights:** Provides a global overview of industrial insect production and notes that environmental performance is a key driver for investment and policy support, with LCAs repeatedly showing advantages over many conventional animal proteins when insects are fed on side-streams.