CLIMATE &
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CLIMATE POLLUTANTS

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TRANSFORMING ORGANIC WASTE WITH BLACK SOLDIER FLIES

A GUIDE FOR DECISION-MAKERS, ENTREPRENEURS, AND IMPLEMENTERS TO UNLOCK THE ORGANIC WASTE POTENTIAL OF BLACK SOLDIER FLY SYSTEMS

PART I

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BACKGROUND TO THE CCAC-TEAP


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The UNEP-Convened Climate and Clean Air Coalition (CCAC) is a partnership of over 200 governments, intergovernmental organizations, and non-governmental organizations. It works to reduce powerful but short-lived climate pollutants (SLCPs) – methane, black carbon, hydrofluorocarbons (HFCs), and tropospheric ozone – that drive both climate change and air pollution.

While the role of carbon dioxide (CO_2) on climate change is well understood, less attention has gone to mitigating non-CO_2 climate pollutants, or "super pollutants", which represent about half of global warming (Ou et al., 2022). Cutting methane emissions in particular is one of the most cost-effective mitigation strategies and would have significant benefits for crop productivity and human health (UNEP and CCAC, 2021). The release of UNEP and CCAC's Global Methane Assessment in 2021 set the stage for the launch of the Global Methane Pledge by CCAC partners the United States and European Union at the 26th Conference of the Parties (COP26), with over 150 countries who have now become part of the collective efforts to reduce global methane emissions by 30% from 2020 levels by the year 2030. On the national level, the CCAC has developed guidance for countries on how to include concrete measures that tackle super pollutants in their Nationally Determined Contributions (NDCs). Reporting both CO_2 and non-CO_2 emissions in NDCs offers countries the greatest mitigation, adaptation and development benefits (see CCAC Guidance for best practices on including methane and other non-CO_2 pollutants into NDCs). To close the knowledge and finance gap for scaling promising, innovative and underfinanced SLCP mitigating technologies, the CCAC established the Technology and Economic Assessment Panel (CCAC-TEAP) in 2023. Cochaired by Ireland and Senegal, CCAC-TEAP was initially piloted to address methane emissions, with the aim of expanding to all major super pollutant emitting sectors.

ABOUT THIS REPORT
BACKGROUND AND SCOPE

The insect industry is booming, with black soldier fly (BSF) technology at the forefront of this revolution. This market, already attracting substantial investment, is addressing some of the biggest global challenges: food security, sustainable agriculture, and waste management. BSF larvae can turn organic waste into high-value protein and soil enhancers, creating a circular economy that is practical, innovative and cost-effective.

While most BSF operations to date have been small to medium-sized, recent investments in larger BSF companies show enormous future potential. The Singapore-based BSF company Entobel has opened a BSF production facility in Vietnam, which is described as one of the largest insect production facilities in Asia. In 2022 they raised over 30 million USD to build a commercial plant with the capacity to produce 10,000 tons of insect meal per year, creating 150 jobs in the region. A BSF factory of similar size was also completed in 2024 in Denmark by Enorm Biofactory, with an investment of approximately 50 million USD.

The potential impact of BSF is not limited to large scale operations. However, around the world, it is smaller and medium-scale BSF ventures that are growing in impact, creating jobs and improving rural food security. These local operations are empowering communities while tackling waste problems head-on. In Africa, for example, insect farming is providing opportunities for women and youth, turning what was once waste into valuable resources. The FAO report ["Mapping of the Black Soldier Fly value chain in East Africa" (Meerts et al., 2023) estimates the number of BSF activities in Kenya alone at 1,200. Many have limited capacity to date, but the figure is a demonstration of the high level of interest and promise in BSF technology.

The market for BSF derived products shows promising growth across various sectors, with applications in aquafeed, livestock feed, and organic fertilizers. Recent reports indicate that the global BSF market, valued at USD 128 million in 2019, is projected to reach USD 3.4 billion by 2030. Small-scale operations targeting niche markets, like pet food (ornamental fish, singing birds), and large-scale facilities producing insect protein for aquaculture and poultry are driving this expansion, supported by increasing demand for sustainable and circular solutions.

The report at hand provides an in-depth overview of the current landscape and potential of BSF technology as a sustainable solution for waste management, animal feed production, and circular economy practices. Developed in response to growing global challenges related to organic waste, food security, and sustainable agriculture, BSF technology has garnered increasing interest from policymakers, investors, entrepreneurs, and agricultural stakeholders alike. BSF bioconversion aligns closely with circular economy principles, offering greater efficiency and value than composting when used under favorable conditions. While composting mainly produces soil enhancers, BSF rapidly transforms organic waste into several high-value products like insect protein, oil for animal feed, and frass as a fertilizer. By addressing both waste reduction and resource recovery, BSF systems provide a scalable, versatile solution with significant economic and environmental benefits.

This report also explores the challenges associated with BSF implementation in diverse settings. In doing so, it aims to provide a balanced perspective on the practicalities and implications of integrating BSF technology, equipping stakeholders with a realistic view of the resources, expertise, and planning needed to successfully adopt and operate a BSF system, be it at industrial scale, as a waste management option for rural towns or when working with smallholder and under-serviced communities generating organic waste.
The report is designed for a broad audience, including decision-makers, entrepreneurs, investors, NGOs, and potential BSF operators and implementers. By introducing system templates—from large-scale industrial models to household setups—the report offers practical insights into the system modules and technological elements needed for different applications. It equips stakeholders with the knowledge to assess BSF systems for waste management, sustainability, and protein production, supporting informed decision-making.

Part I covers the key aspects of BSF technology, including its biology, practical applications, operating models, and the impact of the legal landscape. It also explores the environmental, ethical, and socio-cultural dimensions of BSF systems.

Building on this foundation, Part II helps readers identify the appropriate combination of technology units for their specific needs. It presents various system templates and describes the elements of individual system modules, outlining their advantages and disadvantages.

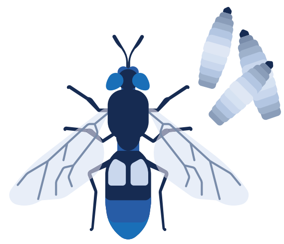
PART I

OVERVIEW OF THE BSF TECHNOLOGY

DESCRIPTION OF THE BSF TECHNOLOGY

Black soldier fly (BSF) technology has become an innovative and sustainable solution for managing organic waste while producing valuable by-products. By converting waste into high-quality protein and nutrient-rich frass, within about two weeks, BSF larvae offers an environmentally friendly approach that supports organic waste reduction (and therefore reduced methane emissions), agricultural sustainability, and new business opportunities. This technology is versatile and scalable, making it suitable for a range of operations, from smallholder farms to large industrial facilities.

KEY ENVIRONMENTAL AND ECONOMIC BENEFITS



BSF technology offers both environmental and economic advantages that appeal to decision-makers, entrepreneurs, and operators alike:

Environmental Impact

BSF larvae can reduce organic waste volumes by up to 80%, diverting waste from landfills and significantly lowering greenhouse gas emissions, particularly methane, which is typically generated by decomposing organic matter in landfills. This technology helps mitigate the environmental impact of waste generation and disposal and contributes to resource efficiency and sustainability goals.

Economic Value

The larvae produced by BSF systems are rich in protein (~35%) and fat (~30%), making them a highly valuable alternative to fishmeal in the animal feed industry. As global demand for sustainable and cost-effective feed sources grows, BSF technology provides an attractive solution. In addition, the by-product—frass—acts as a nutrient-rich soil conditioner, providing a secondary revenue stream for operators in the agricultural sector.

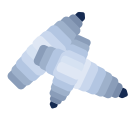
BSF LIFE CYCLE AND FACILITY REQUIREMENTS

The life cycle of the black soldier fly plays a crucial role in optimizing production and efficiency in BSF facilities. Understanding and managing the life cycle stages – egg, larva, prepupa, pupa, and adult fly – helps operators maximize the productivity of their systems.

Egg to Larva Stage

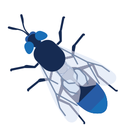
Adult female BSF lay between 300 and 800 eggs in the vicinity of decaying organic material. The eggs hatch within 2–3 days, and the larvae immediately begin feeding. This stage is critical for waste consumption, as the larvae can break down a wide variety of organic materials, converting them into valuable biomass.

Larva to Prepupa Stage



Over the course of 10–14 days, larvae grow from less than a millimeter to 2.5 cm in length. During this period, they consume large amounts of organic material, increasing their biomass and nutrient content. At the end of the larval stage, they enter the prepupal phase, where they stop feeding and seek out a safe place to pupate.

Pupal Stage to Adult Fly



After the pupal stage, which lasts about two weeks, adult flies emerge and are ready to mate within hours. The adults do not feed and live solely to reproduce, completing the life cycle in about a month under optimal conditions.

For the commercial use of the fly, the natural conditions are influenced and changed to such an extent that the cycle can be completed under optimal conditions, thus providing the greatest possible benefit for the operator of the facility. BSF facilities must thus adapt physical domains (Table 1) to the needs of the animals.

FIGURE 1 Life cycle of the black soldier fly, *hermetia illucens*

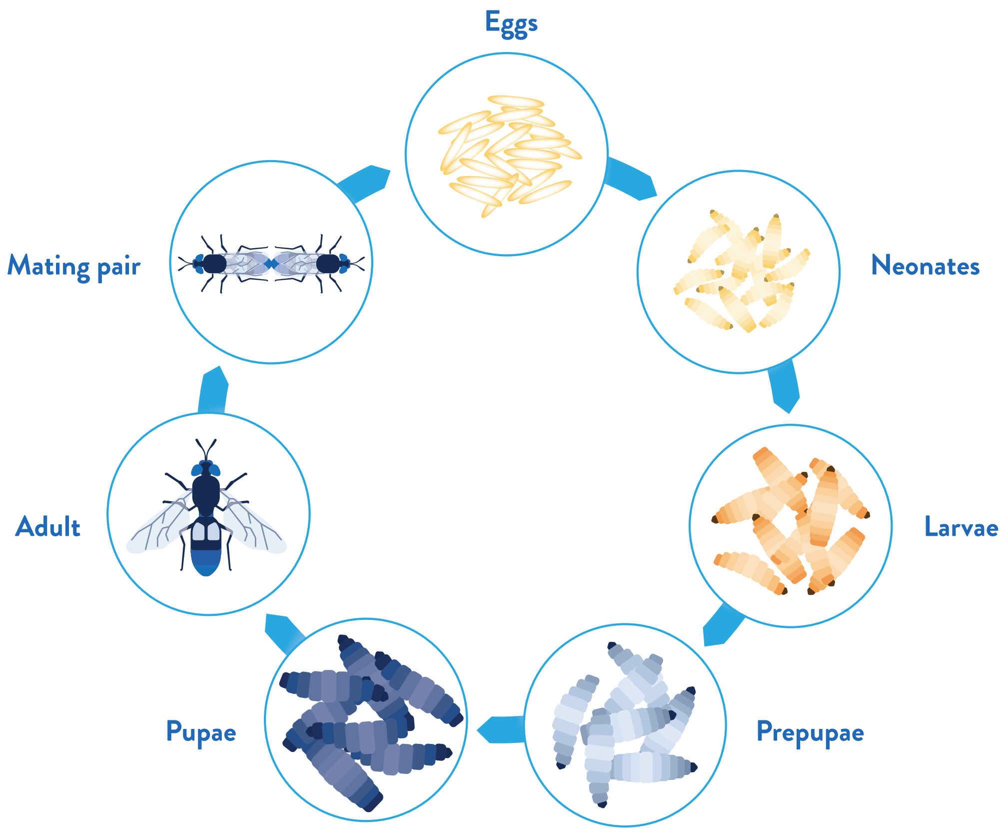


TABLE 1 Essential physical domains for BSF facilities

Physical domain	Requirements
Nutrition	Larvae require free access to sufficient suitable food which provides them with enough nutrients to grow.
Physical environment	BSF larvae thrive in temperatures between 25°C and 30°C, with humidity levels around 60–80%. In temperate regions, heating, ventilation, and air conditioning (HVAC) systems may be needed to maintain these conditions.
Health	A good hygiene level needs to be maintained to ensure absence of disease-causing agents (entomopathogenic fungi, viruses), predators, and parasitoids. The feed cannot contain contaminants (heavy metals, insecticides).
Behavioral interactions	The layout of the reproduction facility should provide enough space for courtship flights and should offer appropriate oviposition (egg-laying) sites.

FEEDSTOCK CONSIDERATIONS

As with other livestock operations, choosing the right substrate for BSF larvae is critical for both the efficiency and sustainability of the operation. BSF larvae are known for their ability to process a wide variety of organic materials, but not all substrates offer the same benefits in terms of growth rate, nutrient content, and ease of processing. Some substrates can be used only in combination with other substrates as their water content or texture is unsuitable if offered alone (Table 2).

Ideal Substrates

Fruit and vegetable waste, agro-industrial by-products, food scraps, and brewer's spent grains are particularly suitable for BSF larvae. These materials are readily available, nutritionally rich, and easy for the larvae to digest, allowing for rapid growth and efficient waste conversion.

Substrates to Avoid

Materials with high cellulose and lignin content, such as wood, straw, and paper, are not digestible by BSF larvae and should be avoided. Additionally, toxic substances like heavy metals, pesticides, and high salt or acid content can harm the larvae, leading to lower productivity and quality.

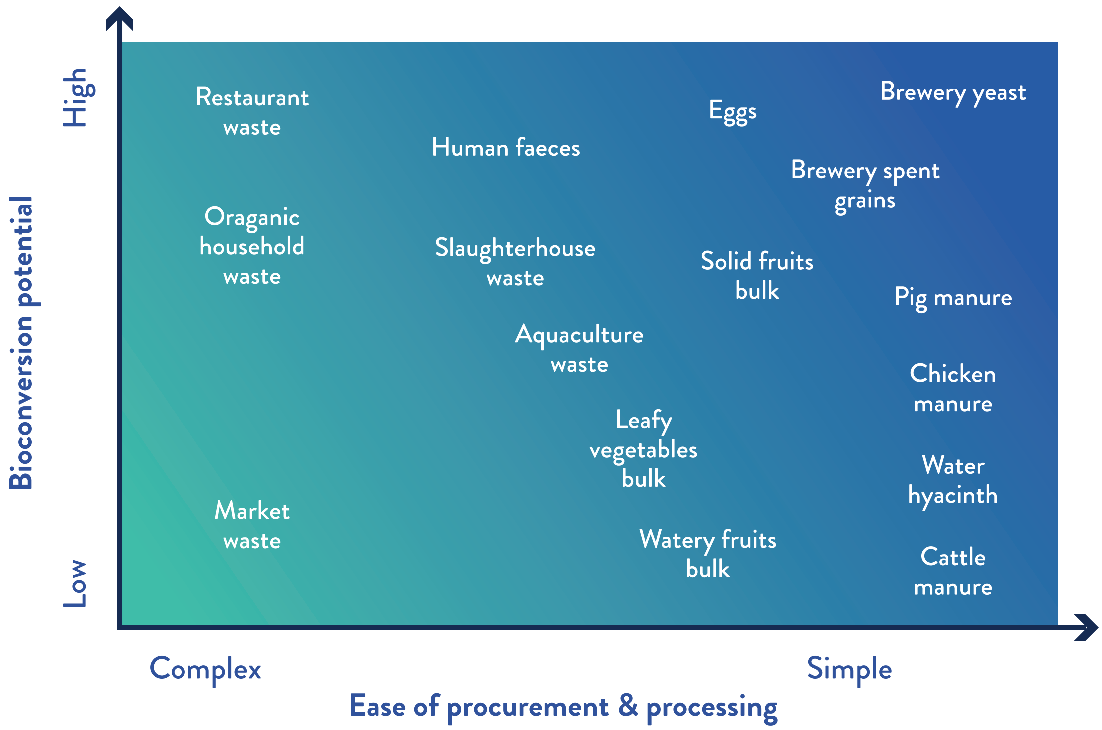
TABLE 2 Substrates to be considered as BSF feed

Stand-alone substrate	Mix-in component	Unsuitable substrates
Fruit and vegetable waste	Brewery yeast	High cellulose and lignin content (wood, straw, paper)
Food waste	Slaughterhouse waste	Inorganic material (plastics, metals, sand)
Organic household waste	Aquaculture waste	Salt-heavy or acidic waste
Brewer's spent grain	Cattle manure	Toxic waste (heavy metals, pesticides, etc.)
Agro-industrial by-products	Dairy waste	
Manure (chicken, pig)		
Nursery waste (eggs, carcass)		

Operators must also consider logistical factors, such as the availability and consistency of feedstock supply. Feedstock is a key resource and should therefore be given high priority within the company. It is advisable to diversify suppliers to a certain extent to minimize dependencies, but it is also important to ensure long-term supply contracts. For example, in an urban context, access to source-separated organic waste from food markets. Furthermore, the seasonality of certain raw materials must be considered. Is the gap between mango harvests to be filled with a substitute substrate, or is the entire operation to be scaled back accordingly? Pre-processing, such as sorting and shredding, may be required to make substrates more accessible for larvae, which can impact overall costs and facility efficiency (Figure 2).

All these factors need to be considered when planning the facility and the geographical location may need to be adjusted according to the substrate supply.

FIGURE 2 Suitability of substrates for BSF facility

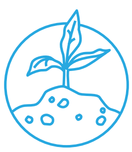


PRODUCTS FROM THE BSF PROCESS

BSF technology offers a range of valuable products, each with distinct market potential depending on local demand, regulatory frameworks, and the specific goals of the operator. Table 3 shows a summary of possible products but can basically be summarized as:

Protein and Fat

BSF larvae are rich in protein and fat, making them a highly sought-after alternative to fishmeal in animal feed. Whether used in aquaculture, poultry, or pet food, the high protein content of BSF larvae offers a sustainable and economically viable feed option. Additionally, the fat extracted from larvae has potential applications in biofuels, cosmetics, and even as a substitute for other animal fats



Frass

The frass produced by BSF larvae serves as a nutrient-dense soil conditioner, improving soil health and promoting sustainable agricultural practices. It contains essential nutrients like nitrogen, phosphorus, and potassium (NPK), making it comparable to compost or biogas digestate. Though frass has traditionally received less attention than larvae biomass, its market potential is growing, particularly in regions with a demand for organic fertilizers.

Chitin, Melanin, and Other By-Products

BSF larvae exoskeletons contain chitin, a valuable biopolymer with applications in the pharmaceutical, biomedical, and agricultural industries. Additionally, melanin, a pigment found in BSF, has potential uses in electronics, cosmetics, and medicine. These by-products offer additional revenue streams for operators looking to diversify their product offerings.

TABLE 3	Products from the BSF process
Product	**Description**
Live/fresh larvae	BSF larvae can be fed live to animals. Because live larvae have a short shelf life (e.g., several days), the distance between the BSF facility and the farmer needs to be short. BSF are live and moving, which is exciting for animals, but can make accurate dosing of feed amounts more difficult.
Frozen fresh larvae/ larval pulp	To make fresh larvae storable, they can be frozen, whole or after mincing. This may be desired in the pet food industry where whole fresh larvae or minced larvae are formulated into wet pet food.
Dried larvae	Fresh larvae are often dried to produce a marketable product with a similar form to other feed ingredients, to reduce storage costs (in comparison to freezing), and to increase shelf life (in comparison to live/fresh larvae).
Protein meal	Larvae can be defatted with wet or dry rendering, similar to fishmeal production. The fat is removed to lower the fat content and thereby increase the protein content, levelling BSF larvae meal composition with feed benchmarks such as soybean meal and fishmeal, which facilitates its inclusion in animal feeds.
Fat	An efficient defatting process with fat filtration can produce a pure, high-quality fat (i.e., > 99% fat) that is high in antimicrobial lauric acid and a similar composition to coconut fat. It can be used as an ingredient for feed, cosmetics, or biofuel production.
Frass	Frass is the product produced in largest amounts in BSF facilities (15–50% of feedstock input at around 50% moisture content) and is often overlooked. However, depending on the local market for soil conditioners and fertilizers and quality of product shown by field trials, some companies could also establish frass as their product with the highest revenue.
Chitin/Chitosan	The exoskeleton of insects contains the polymer chitin (larvae: 8–12% dry mass; exuviae: 22–26% dry mass). However, chitin in feed can have negative effects on the growth of livestock such as fish, poultry, and pigs. For insect producers, it may therefore be desirable to extract chitin from the larvae and find a separate market.
Melanin	All BSF life stages contain the high molecular weight pigment, melanin. It serves as an antioxidant and gene-protecting agent, possesses antimutagenic properties, and can absorb heavy metals and neutralize lipid peroxidation products. Melanin can also be seen as a natural semiconductor and therefore may find its application in biodegradable electronic devices in medicine or non-recoverable monitoring gadgets in sensitive environments.
Biochar	Biochar can be produced from pyrolysis of organic material, e.g., BSF frass. Biochar can be used as a soil conditioner or the char can be briquetted to substitute wood-based charcoal, one of the most common cooking fuels worldwide. Pyrolysis is an established technology at industrial scale for other organic materials.
Biogas	Depending on the feedstock and rearing process conditions, frass from BSF larvae rearing can still produce relevant amounts of biogas in anaerobic digestion. Biogas production from food waste BSF frass may produce 550 m^3/ton with a methane percentage of 61% as compared to 700 m^3/ton and 64% for the original food waste.

BSF MARKETS

Like the BSF technology itself, the market for BSF products is still in its early stages and faces significant uncertainties. Prices for these products are difficult to narrow down, as they depend heavily on local factors, and markets, and the level of processing involved. Typically, BSF products are priced in line with the commodities they aim to replace or supplement. For instance, dried larvae and protein meal, which contain 45–60% protein, are priced similarly to fishmeal and other animal meals, ranging from approximately USD 1,500 to 2,000 per ton (e.g., USD 1,700 per ton for fishmeal, as of April 2024). The price of BSF fat depends on its quality, such as purity and fatty acid composition, allowing it to serve as a substitute for cooking oil, vegetable fat, soy, coconut, or poultry fat, with prices ranging from USD 900 to 2,500 per ton. As for frass, it is typically compared to compost or other organic soil amendments (Diener & Gold, 2022). While animal feed is in demand at a constant level throughout the year, seasonality can pose a challenge for BSF producers when it comes to the application of soil conditioners. They must then have sufficient space for the storage of the finished compost.

One major challenge for BSF companies is keeping production costs low enough to compete with conventional products such as fishmeal, soymeal or compost. This is partly because the industry is still refining its production processes, with a steep learning curve for optimizing efficiency through technological advancements and improved standard operating procedures. Additionally, strict regulations in some countries restrict the use of some waste materials as feed, undermining one of the key advantages of BSF technology – converting otherwise worthless organic material into valuable products (Mouhrim et al., 2023).

To compete with established products, BSF companies often highlight the added value their products bring, such as reputation for sustainability, improved animal welfare, and enhanced functionality. However, conventional aquaculture and livestock farmers remain highly price sensitive, as feed costs account for the largest expense in their operations. Unless these costs can be passed on to end consumers, it can be challenging to compete on price. This price sensitivity, along with the legal landscape, has contributed to the pet food market being the most competitive for BSF companies, especially in Europe. Pet owners tend to value sustainability and the additional benefits of ingredients, such as hypoallergenic properties, making them more willing to pay a premium (Fantechi et al., 2023; Siddiqui et al., 2022). More detailed insights into current market trends and future developments are available in the chapter "Market Opportunities and Barriers."

In recent years, frass has gained attention due to its consistent production in BSF waste treatment facilities, its richness in plant nutrients, and its potential to generate revenue in the agribusiness sector. However, it has not received as much focus as larval biomass, and there are still gaps in knowledge about its applications and benefits for farming and cultivation activities.

Ultimately, which product should be produced depends on market demand. If the larvae and frass are not intended for on-farm use, it is essential to conduct a market analysis to identify potential products that BSF production could replace. This will help determine the appropriate price range and allow for the development of a business plan that balances projected sales with maximum production costs.

Further reading:

- Diener and Gold (2022), Global Study on Black Soldier Fly Sector
- Dortmans et al. (2021), Black Soldier Fly Biowaste Processing – A Step-by-Step Guide
- https://bsfl-substrate-navigator.onrender.com/

KEY CHALLENGES

BSF technology is basically no different from animal husbandry as we know it from pig or chicken farming. The only difference is that these industries have an 80- or 100-year lead in experience. It should therefore come as no surprise that a lack of experience and a lack of comparative cases continue to pose a major challenge in achieving profitability and sustainability.

1. **Scaling Challenges**

   Many insect companies face difficulties in scaling their operations from small pilot projects to industrial-scale production. Rapid scaling often leads to inefficiencies, high capital expenses (CapEx), and design errors that make it hard to pivot or adjust once infrastructure is built.

2. **Feedstock Supply and Quality**

   The availability and consistency of feedstock play a crucial role in the performance and profitability of BSF companies. Sourcing feedstock at a low cost, ensuring it is nutrient-rich, and securing a stable supply chain are recurring issues across the industry.

3. **Technological Complexity and Costs**

   The insect production process involves a lot of technical steps, from breeding and harvesting larvae to extracting protein, oil, and frass. High-tech automation systems, especially those sourced from Europe, are often expensive and difficult to maintain.

4. **Regulatory and Market Acceptance**

   The market for insect protein, oil, and frass faces significant regulatory hurdles, particularly in regions like Europe and North America. Stricter regulations on feedstock use and selling insect-derived products have slowed down market penetration. Regulatory frameworks can be inconsistent across countries, creating further barriers.

5. **Investor Sentiment and Financial Viability**

   Many early-stage insect companies have been supported by venture capital, but some of these companies have failed to deliver on their promises due to poor strategic choices. This has resulted in a "wait-and-see" approach from investors, where there's reluctance to fund new players in the market.

6. **Economic Sustainability**

   While BSF technology promises sustainability, the industry's success depends largely on economic efficiency. Many companies have yet to reach the profitability needed to compete with alternative protein sources like fishmeal or soymeal. High energy and operational costs, especially in non-tropical climates, exacerbate these challenges.

In Europe and North America, the focus is on cutting expenses related to feed and energy, driven by strict regulations on allowable substrates for insect rearing and the need for full climate control in temperate regions. Heat recovery from the farm could provide economic and ecological relief and will need to be considered in more detail in the future. However, the insect industry is only in its infancy and systems and their components still need to be individually adapted to local conditions, if not developed from scratch. Due to the competitive situation, cross-industry exchange is understandably limited, which increases the importance of having your own R&D departments and significantly increases costs, especially in the start-up phase. Also, many waste management companies focus on short-term shareholder profits rather than investing in technologies like BSF, limiting the industry's potential for growth (Hoang & Nguyen, 2024). To overcome these challenges, a cultural shift is needed, prioritizing environmental protection and encouraging companies to focus on sustainability, which could lead to greater revenue, helping to grow jobs and attract public investment.

In tropical countries, the costs of air conditioning are less of a priority. In most cases, ventilation systems are sufficient to ensure constant production. Reliable access to a constant substrate source of reliable quality, however, is more challenging due to competition with other uses. There are often functioning value chains for the "pure" organic waste sources such as fruit and vegetable waste, restaurant waste, or even chicken manure. BSF industries should not compete with these channels either and should leave them to existing customers, often pig and chicken farmers. In many cases, the sourcing of substrate therefore includes a step that sorts collected material (from public markets, restaurants, or even households) and disposes of the rejected fraction separately. These additional costs must be considered, but these waste management-related activities might also open opportunities in the form of Public-Private partnerships (PPPs).

Reproduction continues to pose major problems for some operators. Unlike bioconversion, reproduction requires the needs of the fly at all its life stages to be met. This means that various types of environmental conditions or habitats must be created so that the animals can pass through their various phases in the best possible way. The process therefore requires a lot of manual handling and tends to be labor intensive. This means that countries with relatively low labor costs have a competitive advantage.

For smallholder BSF farmers in Kenya, increasing substrate availability directly improves gross margins by boosting larvae production. However, when farmers spend more time managing the facility, operational costs rise, reducing profitability. This indicates that while higher production is achievable with ample substrate, the efficiency of facility operations is critical to maintaining strong margins (Mutuku et al., 2022). It is therefore important to implement a standard operations protocol that integrates BSF farming into the daily or weekly schedules of farmers, allowing them to run it as a side business—similar to beekeeping. Optimizing labor, streamlining processes, and ensuring a steady substrate supply are essential for smallholders to maximize their economic returns in BSF farming.

Possible approaches to overcoming the difficulties are:

Incremental Scaling and Modularity

Instead of rushing into large-scale facilities, companies should adopt a modular, incremental scaling approach. This allows them to learn from smaller-scale operations, improve processes, and reduce risks without committing excessive capital up front.

Efficient Feedstock Management

Companies should source waste feedstocks that are consistent, nutrient-dense, and ideally free or low cost. Partnerships with industries producing large volumes of organic waste (e.g., food processors, breweries) can reduce costs and secure a steady feedstock supply.

Simplified Technology and Infrastructure

In climates suitable for BSF production, companies can lower costs by using simpler infrastructure. Avoiding over-engineered systems and opting for cheaper alternatives like agri-equipment can help achieve scalability more affordably. Where land prices allow, vertical densification (racking/shelving) can be avoided, which can massively reduce investment costs for equipment.

Regulatory Engagement and Market Diversification

Companies need to work closely with regulators and industry associations to help shape favorable policies for the insect protein industry. Diversifying products (e.g., targeting aquaculture, pet food, or bioconversion) can open new markets and reduce reliance on regulatory approvals for each product.

Strong Business Planning and Investor Communication

To regain investor confidence, insect companies should focus on realistic business plans that demonstrate profitability and economic efficiency. Techno-economic analysis (TEA) can be used to compare insect protein production against traditional protein sources, showing the financial viability of the business.

In any case, a balance must be found between automation, strict operational protocols, reasonable monitoring, and the courage to accept imperfections.

Further reading:

- Badeski (2023), Investment insights for the insect industry
- van Huis (2022), Edible insects: Challenges and Prospects
- Mutuku et al. (2022), Determinants of profitability of black soldier fly farming enterprise in Kenya
- Jong and Nikolik (2021), No Longer Crawling: Insect Protein to Come of Age in the 2020s

CHOOSING THE RIGHT SYSTEM

When trying to select the right system, an overview of what is available can be useful. We distinguish between **system templates**, where the critical factors are primarily technology-driven, and **operational models** (see below), which are influenced more by business model considerations. Key factors in choosing the appropriate system template include the degree of product processing, the size of the facility, the level of mechanization, and the specific facility units requiring climate control. These factors directly impact both capital expenditures (CAPEX) and operational expenditures (OPEX), making the choice of system a crucial decision for balancing costs and achieving operational efficiency.

Selecting the appropriate black soldier fly (BSF) system template is crucial for ensuring its feasibility, efficiency, and sustainability. Understanding the specific local conditions, available resources, and operational goals allows stakeholders to choose a system that aligns with their needs. For a farmer in a tropical region with low labour costs and agricultural waste available, a simple, decentralized system requiring minimal infrastructure may suit this situation. In contrast, an operation in a temperate region with a strict legislative framework and expensive labour might opt for an automated, industrial-scale system to ensure compliance and efficiency. A mismatch between system design and local conditions can lead to inefficiencies, underperformance, and financial losses.

SYSTEM TEMPLATES

Six different systems which cover the largest part of different BSF setups were identified.

SYSTEM 1
Micro-Scale Home System

SYSTEM 2
Simplified BSF Approach SIMBA

SYSTEM 3
Centralized Facility in Tropical Regions

SYSTEM 4
Container-Based/Decentralized System

SYSTEM 5
Centralized Medium-to Large-Scale Facility

SYSTEM 6
Large-Scale Industry Pioneers

A system consists of a series of **system modules**. Each of these system modules comprises a selection of technology options, bundled by **process steps**. In addition to the system modules that are strung together in the production chain, there are also **intersecting system modules** that can affect several areas (Figure 3).

The intersecting system modules are:

- CLIMATE CONTROL SYSTEMS (HVAC)
- MONITORING SYSTEMS
- BUILDING STRUCTURES

These groups must be considered across different units of a BSF system, and necessity and their degree of complexity depend on the system applied and the conditions under which the system should be run.

KEY FACTORS

DEGREE OF PRODUCT PROCESSING

To a large degree, this depends on the identified market. In many cases, it is possible to keep the post-treatment of the products to a minimum. This means that larvae are fed live to animals and the frass can be applied directly to the field after it has been composted. This has a major impact on the degree of technology required and the cost. On the other hand, storability of the larvae will be a challenge. As soon as large quantities are produced or the products enter a standardised value chain, processing the products into a more storable version is unavoidable.

RANGE

- **Low:** no processing/live larvae
- **Medium:** drying and composting
- **High:** fractionation of the individual components (oil, protein) and extraction of specific substances (melanin, chitin)

SIZE OF THE FACILITY

The size, or rather the capacity of a plant, has a major influence on how a plant can be operated. In addition to the internal handling of materials (pre-processing, conveyance, feeding and harvesting mechanisms), delivery and storage also come into play.

RANGE

- **Small:** up to 50kg/day
- **Medium:** 5-30 tons/day
- **Large:** >150 tons/day

DEGREE OF MECHANIZATION

Even a facility that processes several tonnes of material per day can be largely operated manually. Which activities are ultimately supported or even replaced by machines also depends on the personnel costs and the available capital.

RANGE

- **Low:** manually operated units
- **Medium:** some areas are supported by technical aids (pre-treatment, conveyance, separation, monitoring)
- **High:** largely automated processes.

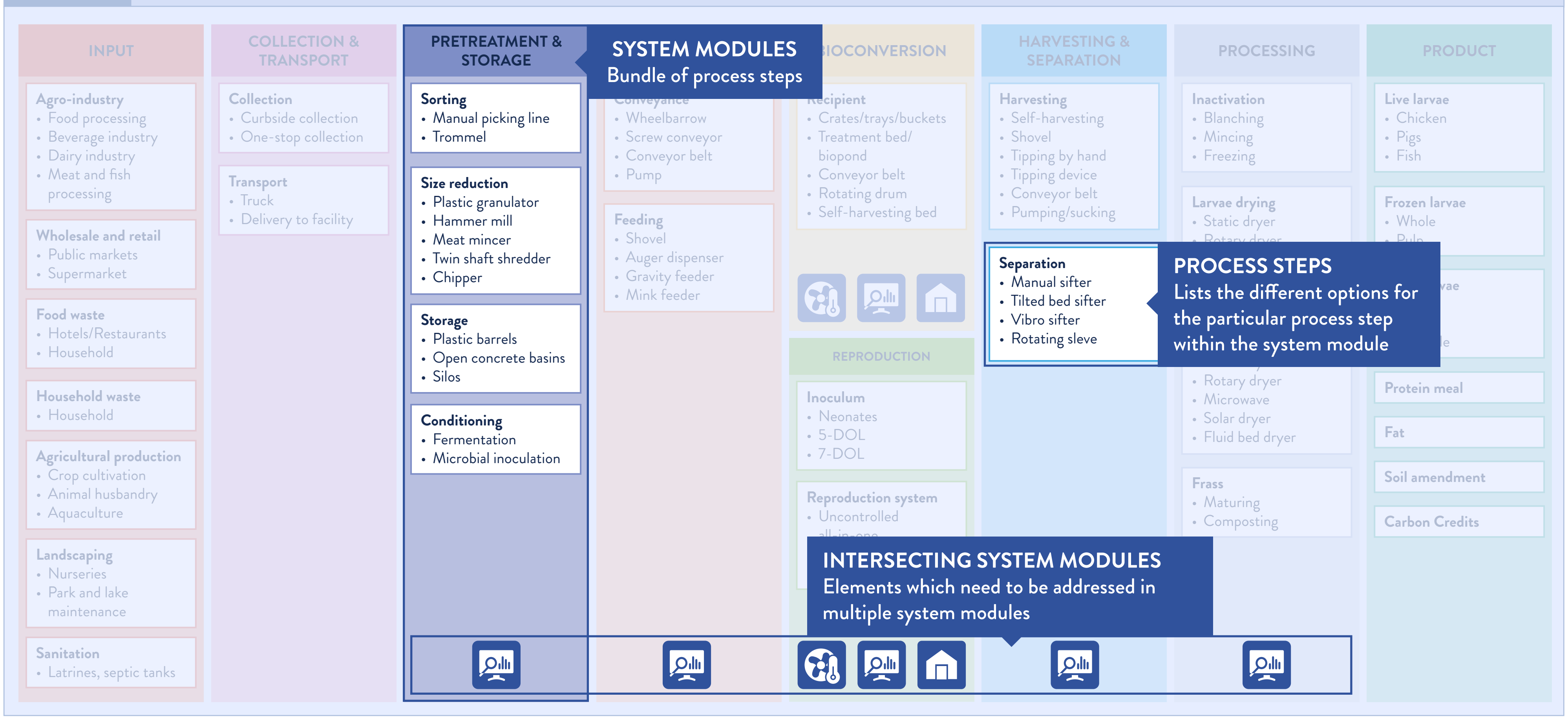
AREAS OF CLIMATE CONTROL

The areas of a BSF facility that need to be cooled, ventilated or heated naturally depends on the climate in which the facility is to be located, but also on the need for constant production. Certain climate conditions are simply hostile to the fly and must therefore be compensated for with climate control units, while others lead to fluctuations in growth or the duration of life stages.

RANGE

- **None:** no climate control measures needed
- **Moderate:** climate control is applied to key functional units (reproduction, nursery)
- **All:** entire facility is climate controlled.

FIGURE 3 The components of a system template



A more detailed description of the individual system templates, as well as the system modules and the associated technologies of the process steps, can be found under the individual links. These technical sheets are intended to help the interested party to put together the system and its individual technology components.

TABLE 4 Short description of the BSF system templates

SYSTEM 1

Micro-Scale Home System

Description

These systems are simple and low-cost, designed for individual use or household needs. Also used for educational purposes, they provide a practical introduction to BSF technology. They are suitable for small-scale waste management in rural and urban areas and backyards. This scale can also support direct use of larvae or frass on-site, making them ideal for schools, or families with backyard poultry

Key factors

Degree of product processing	Low ■□□□□ High	
Size of facility	Small ■□□□□ Large	
Degree of mechanization	Low ■□□□□ High	
Areas of climate control	None ■□□□□ All	

Estimation of costs per ton of input

	Resources per ton of input (Low ⟷ High)		
Capex	Infrastructure	□□□□□	$0 - 5
Capex	Equipment	■□□□□	$30
Opex	Personnel	■□□□□	1 FTE
Opex	Consumables	■□□□□	$5 - 22
Opex	Maintenance	■□□□□	$5 - 10

SYSTEM 2

Simplified BSF Approach SIMBA

Description

This model caters to small-scale operations, such as rural entrepreneurs and smallholder farmers. It focuses on replicable processes that are easy to manage without requiring advanced infrastructure or expertise. These systems leverage local resources and waste streams, enabling farmers to create a side business by selling larvae or using them as animal feed.

Key factors

Degree of product processing	Low ■■□□□ High	
Size of facility	Small ■■□□□ Large	
Degree of mechanization	Low ■□□□□ High	
Areas of climate control	None ■■□□□ All	

Estimation of costs per ton of input

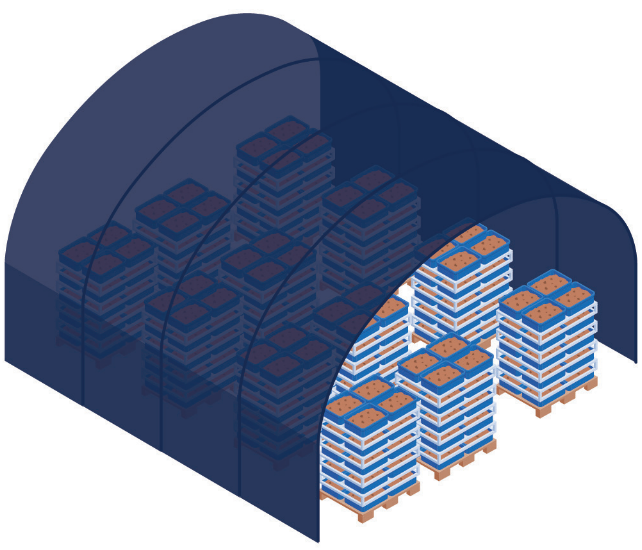
	Resources per ton of input (Low ⟷ High)		
Capex	Infrastructure	■■□□□	$250 - 1,000
Capex	Equipment	■■□□□	$70 - 200
Opex	Personnel	■■□□□	1-2 FTE
Opex	Consumables	■□□□□	$5 - 10
Opex	Maintenance	■□□□□	$2 - 4

SYSTEM 3

Centralized Facility in Tropical Regions

Description

This system is designed for warm climates, where natural conditions reduce the need for expensive climate control. They can process large volumes of organic waste from various sources, such as municipal waste, markets, and agricultural by-products. These facilities often adopt low-cost infrastructure, such as simple treatment beds, and can serve as hubs for waste collection and BSF production. Facilities like **Bioconvision in Uganda, LimaDOL in the Philippines or Chanzi in Tanzania** are examples for such facilities.



Key factors

Degree of product processing	Low ■■■□□ High	
Size of facility	Small □■■■□ Large	
Degree of mechanization	Low □■■□□ High	
Areas of climate control	None ■■■□□ All	

Estimation of costs per ton of input

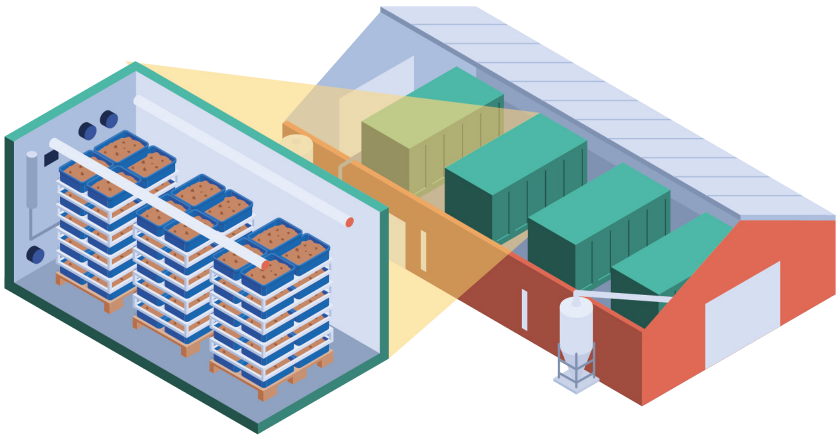
	Resources per ton of input (Low ⟷ High)		
Capex	Infrastructure	■■■□□	$3,000 - 15,000
Capex	Equipment	■■■□□	$1,000 - 5,000
Opex	Personnel	■■■■□	2-5 FTE
Opex	Consumables	■■□□□	$5 - 25
Opex	Maintenance	■□□□□	$2 - 7

Description	Key factors	Estimation of costs per ton of input

SYSTEM 4

Container-Based/Decentralized System

Modular and mobile, these systems allow for flexible waste management in urban or semi-urban areas. Containers can be deployed at different locations, processing waste close to its source. This reduces transportation costs and emissions while enabling efficient waste treatment. Such systems are particularly useful for businesses or municipalities with distributed waste sources. **Reploid** for example takes advantage of empty agricultural structures to turn them into decentralised BSF facilities. Other examples for decentralised systems are F**lybox, LIVIN farms, or Manna Insect**



Key factors

Degree of product processing	Low	■■■■□	High
Size of facility	Small	■■□□□	Large
Degree of mechanization	Low	□■■■■	High
Areas of climate control	None	□□■■■	All

Estimation of costs per ton of input (Resources per ton of input: Low ⟷ High)

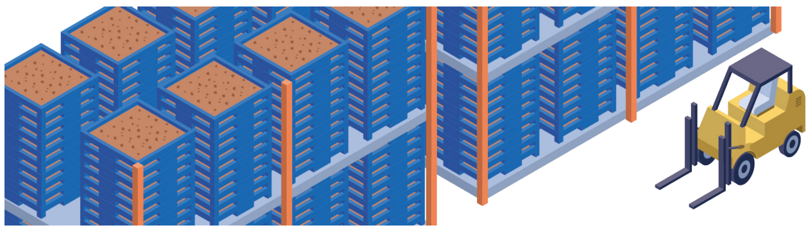
Capex	Infrastructure	■■■□□	$0 - 10,000
Capex	Equipment	■■□□□	$50 - 2,000
Opex	Personnel	■■□□□	1 FTE
Opex	Consumables	■■■□□	$25 - 40
Opex	Maintenance	■■□□□	$10 - 20

Description	Key factors	Estimation of costs per ton of input

SYSTEM 5

Centralized Medium-to Large-Scale Facility

These systems handle significant waste volumes and require standardized processes, such as automated feeding and harvesting. They are suited for urban or industrial areas where waste generation is high, and markets for BSF products are accessible. While they require substantial investment, they achieve economies of scale and produce consistent outputs, making them attractive to investors. The Chilean company **F4F** for example, treats about 30 tons of waste per day. Also **Entobel in Vietnam and Chanzi in Tanzania** represent this type of system



Key factors

Degree of product processing	Low	□□■■■	High
Size of facility	Small	□□■■■	Large
Degree of mechanization	Low	□□□■■	High
Areas of climate control	None	□□□■■	All

Estimation of costs per ton of input (Resources per ton of input: Low ⟷ High)

Capex	Infrastructure	■■■■□	$10,000 - 30,000
Capex	Equipment	■■■■□	$5,000 - 8,000
Opex	Personnel	■■■□□	2-3 FTE
Opex	Consumables	■■■■□	$50 - 100
Opex	Maintenance	■■■□□	$30 - 50

SYSTEM 6

Large-Scale Industry Pioneers

These high-tech, automated facilities are the epitome of industrial BSF production. Designed for maximum efficiency, they incorporate cutting-edge technologies such as robotics and advanced climate control. They cater to large-scale operations targeting international markets, such as aquafeed manufacturers or pet food companies. These facilities demand significant expertise and investment but promise high productivity and profitability. Representatives of this category are **Agronutris, Protix, or EnviroFlight.**

Key factors

Degree of product processing	Low	□□□■■	High
Size of facility	Small	□□□■■	Large
Degree of mechanization	Low	□□□□■	High
Areas of climate control	None	□□□□■	All

Estimation of costs per ton of input (Resources per ton of input: Low ⟷ High)

Capex	Infrastructure	■■■■■	$20,000 - 50,000
Capex	Equipment	■■■■■	$15,000 - 20,000
Opex	Personnel	■□□□□	0 - 1 FTE
Opex	Consumables	■■■■□	$50 - 100
Opex	Maintenance	■■■■□	$50 - 100

OPERATIONAL MODELS

Other than the operational system, the way one operates a BSF business depends mostly on external factors rather than technical considerations. The choice of the model depends on factors such as available capital, local waste sources, market demand for BSF products, and regulatory conditions. Personal preference and motivation should not be ignored either. Each model offers unique opportunities for entrepreneurs and individuals to integrate BSF technology into waste management systems while creating sustainable, profitable ventures.

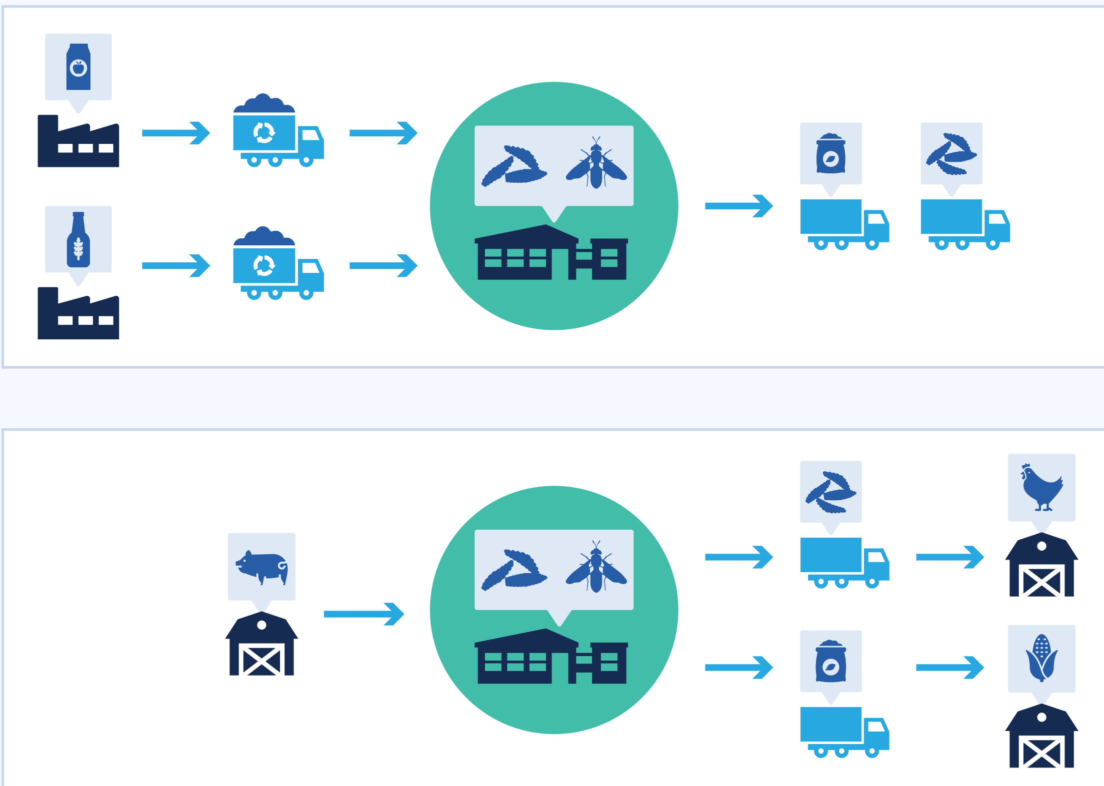
PRODUCTION MODELS

Centralized

The entire processing chain takes place in one location. This means that the substrate is collected from one or more waste producers and processed centrally. This approach allows substrates from different suppliers to be mixed in an optimal and constant ratio. Furthermore, the economy of scale principle applies to individual components of the plant. However, it should be noted that organic waste usually consists of 70–80% water and that transport costs are therefore significant. A large-scale centralized plant is therefore only recommended in close proximity to the substrate supplier. Alternatively, the substrate can be delivered in dry form and the water added on site or a waste acceptance fee is charged.

FIGURE 4

Centralized operations with a large industry waste producer (left) and in a farming setting (right). All substrate is being treated in one location where small larvae are also being produced. In the case of the farm, the products could also be used on-farm directly

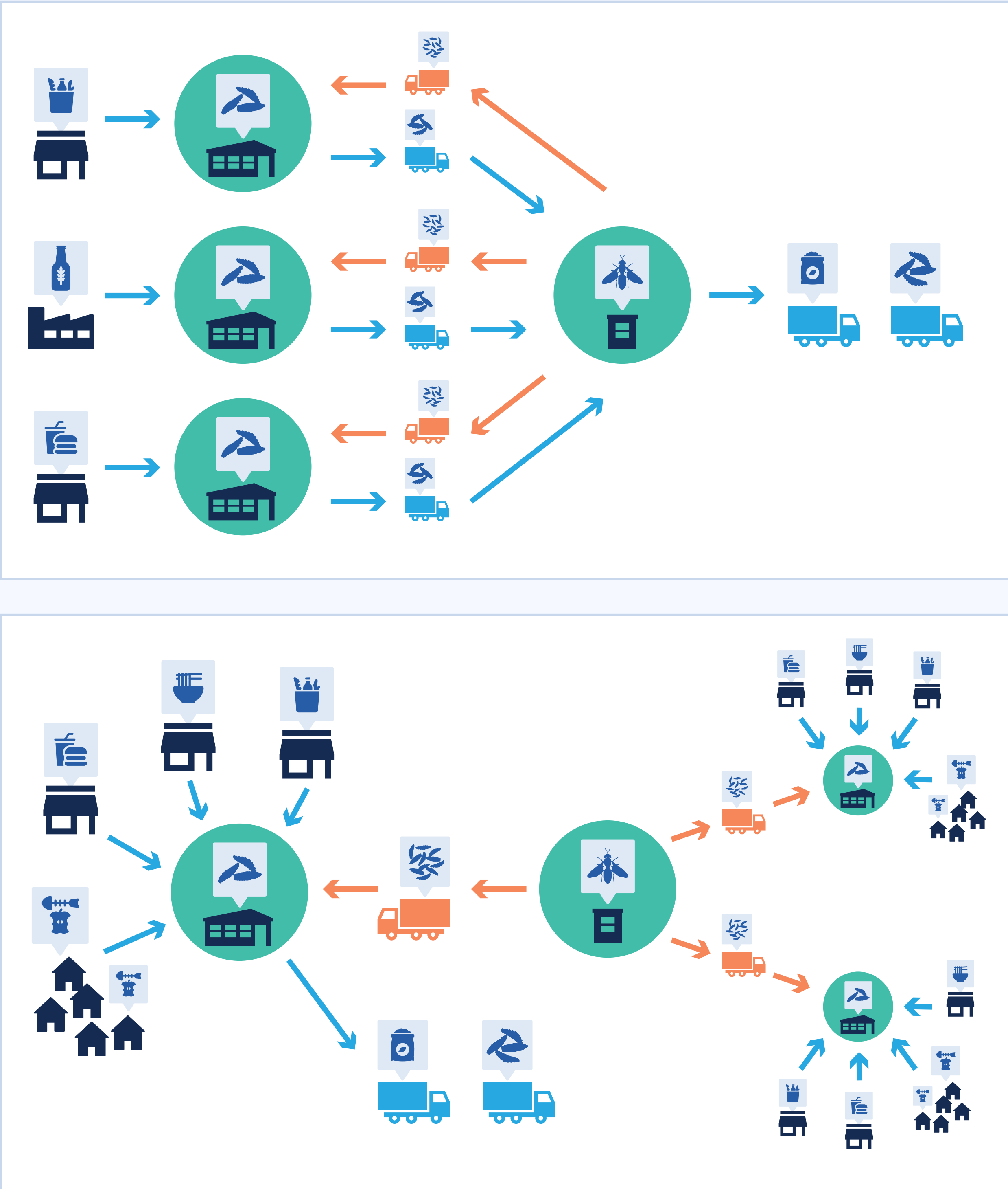


Decentralized

The treatment takes place either at the waste producer's premises or the substrates are collected within a limited radius and treated at one location. The young larvae are delivered from a central production site. The products (larvae and frass) are usually processed centrally. This form of organization limits transport to the delivery of young larvae and the collection of the products.

FIGURE 5

Decentralized operations with treatment at the waste producers' premises (above) and with collection centers (below). The collection centers can for example be municipal waste collection stations scattered all over the city.



The choice of the operating model depends largely on the transport costs and the existing offers from providers for maggot production and product processing. In many cases, it may be worthwhile to operate all units yourself, even if they are not in the same geographical location.

Ownership issues also need to be considered. In the case of a decentralized model, who owns the bioconversion unit? Is a unit sold directly to the waste producer, or should it remain the property of the BSF facility operator but be operated on the waste producer's property?

BUSINESS MODELS

There are various business models in terms of how BSF operates in the value chain (adapted from Diener and Gold (2022)):

Animal Feed Production

Focused on producing high-quality insect protein and frass as sustainable alternatives to fishmeal and soymeal. These companies typically use high-value, homogenous, organic by-products as feedstock to ensure product consistency and reduce environmental impacts. Especially for farmers, the use of the products within their own agricultural operation may cut a lot of production costs. Any surplus can always be sold to neighbors or at the local market. Even the substrate can often come from the grower's own farm. This eliminates the substrate procurement costs.

Waste Management

BSF companies focus on reducing biowaste mass and volume by converting diverse waste streams, such as animal manure and food waste, into larvae and compost. These companies often get paid for waste treatment but face challenges like lower product consistency and more complex technology requirements. Yang-Jie et al. (2023) describe a profitable facility in China which treats 15 tons of municipal organic waste per day. Although the facility could be run with a profit without the subsidies, the USD 25/ton provided by the local government makes the operation even more attractive. In many countries, commercial and industrial businesses are required to dispose of their waste properly. In those cases where this regulation is enforced, opportunities arise for BSF operators to accept and treat these substances for a fee. Environmental services such as the collection and disposal of invasive water hyacinth, *Pontederia crassipes*, or the controlled disposal of expired food from the World Food Program also represent potential sources of income for BSF facilities.

Young Larval Offspring

This model separates BSF reproduction from bioconversion. Specialized breeders supply young larvae to bioconversion companies, potentially reducing initial costs and specialized knowledge requirements for the latter. However, it creates dependency on breeders and faces logistical challenges in transporting live larvae.

High-Value Products

Some companies focus on extracting higher-value compounds from BSF, such as chitin, melanin, or products for pharmaceuticals and cosmetics, rather than selling basic larvae or protein meal.

Smallholder Farmers

Small-scale, low-tech BSF systems allow smallholder farmers to convert household waste into chicken feed. These models are common in Sub-Saharan Africa and South-East Asia but often face operational challenges due to the technical demands of BSF farming.

Carbon Credits

By diverting waste from landfills and thus reducing methane emissions, BSF facilities can potentially earn credits that are sold in carbon markets. This option not only supports environmental goals but also provides financial incentives to offset operational costs, particularly in large-scale BSF facilities focused on waste management. Efforts are underway to have the methodology certified. For companies, this is a long and expensive road (135,000 USD, 2.5 years, *personal communication*), but one that can be extremely lucrative if successful.

In principle, we can see a tendency towards diversification in the BSF sector, as we can see in other agro-industrial sectors such as poultry or pig production. Chicks are delivered by a company, fattened to slaughter weight, and finally delivered alive to the slaughterhouse. Additionally, in horticulture, we see many companies that buy their seeds or even seedlings from one company and outsource further processing after harvesting to another company.

CASE SNAPSHOT | **Waste management and carbon credits**

Chanzi, a BSF company operating in Tanzania and Kenya centered a model around waste management in combination with an attached waste recycling operation combines BSF bioconversion and income generation with carbon credits. Apart from the organic material collected from producers like breweries, the abattoir or hatcheries, Chanzi sources organic waste also sourced from markets by financially incentivizing informal waste pickers to collect waste. Additionally, non-food organic waste (branches, leaves) is used to produce biochar, improving substrate structure in the BSF process and integrating it into a carbon credit scheme. Through pioneering carbon credit for BSF, the profit margin has been raised from a breakeven level to a healthier percentage.

Around 75 tons of waste is being processed daily which yields 1-2 tons of dried larvae, balancing site-level break-even. With low land and labor costs, the operation relies on straightforward infrastructure like walk-in cages and simple treatment beds. Time-stamp photo verification ensures compliance with standard operating procedures, significantly boosting output.

THE NEED FOR A STRONG REGULATORY FRAMEWORK

Since insect farming is a relatively new technology, most regions lack insect-specific regulations, leaving black soldier fly (BSF) operations in a legal grey area or under general livestock laws. While this provides operational flexibility, the absence of clear standards for quality, hygiene, and environmental impact poses long-term challenges for building stability and ensuring compliance in the sector. Understanding and navigating the existing regulatory landscape is therefore critical for BSF operators, particularly in terms of production costs, market access, and scalability.

BSF operations are affected by a range of regulations spanning food safety, veterinary standards, environmental protection, waste management, and business development. Below are key regulatory areas influencing BSF systems:

Farming and Feed

The legislation surrounding the use of waste as feed for insects and the feeding of insects to animals is in place to protect against health risks, ensure food safety, and prevent environmental damage. These regulations are particularly important for maintaining the integrity of the food supply chain and preventing outbreaks of disease or contamination. BSF farming is therefore typically regulated in the same way as livestock farming unless specific insect legislation exists. This affects key aspects of the operation:

- **Feed Substrates:** Regulations often dictate what can be fed to larvae. For example, some regions restrict the use of restaurant waste, slaughterhouse by-products, or supermarket surplus as feed. In areas where insects are not classified as livestock, more flexible options, such as animal manure, may be allowed. These restrictions have significant implications for operational costs and sourcing materials.

- **Use of Larvae in Feed:** While BSF larvae are a natural part of many animals' diets, regulations may still define whether they can be used in feed for livestock, along with requirements for processing, packaging, and labeling. For example, certain markets like the European Union may restrict the use of raw larvae and demand specific processing standards, which can affect the commercial viability of BSF products.

- **Killing and Handling of Larvae:** Research into the pain sensitivity of insects is ongoing and regulations regarding the ethical handling and humane killing of larvae are beginning to emerge. In regions with established guidelines, operators need to ensure compliance with these standards to avoid legal issues.

- **Frass as a Soil Amendment:** If frass (the by-product of BSF operations) is to be sold as a soil amendment or fertilizer, it must meet local standards for compost or biogas digestate. This includes meeting specific requirements for nutrient content (NPK), impurities, and heavy metal levels, as well as obtaining necessary certifications to legally sell frass as an agricultural product.

Waste Management and Circularity

- Many countries are integrating the circular economy into their environmental policies, opening opportunities for BSF projects, even if insects are not explicitly mentioned. As BSF operations reduce organic waste and promote recycling, they may align well with policies on sustainable waste management, potentially unlocking funding or support from government programs.

- However, operators in the waste management sector typically need licenses to process waste. BSF facilities handling organic waste may need to obtain similar permits to ensure compliance with local regulations and to operate legally.

Climate Mitigation

- While there are currently no established regulations that explicitly link BSF operations to reduction of greenhouse gas (GHG) emissions, BSF systems do contribute to climate mitigation by diverting organic waste from landfills, thus reducing methane emissions. This potential makes BSF operations well-suited to be incorporated into national climate policies, especially those aligned with the Paris Agreement or other sustainability frameworks. Governments advancing climate action may begin to recognize BSF as a tool for achieving GHG reduction targets.

Business and Innovation

- As an emerging industry, BSF operations may also be subject to broader regulations governing new business areas and socio-economic development. This includes laws related to innovation, market creation, and intellectual property for new technologies. Additionally, operators must adhere to health and safety standards for workers, especially when dealing with organic waste and live animals.

Examples of International Regulatory Approaches

Each country handles insect farming regulations differently, though many regions are making efforts to develop or refine their frameworks. Below are a few examples of national and regional approaches:

- **CHINA:** China's feed materials catalogue includes listings for "insect meal" and "de-fatted insect powder." In both cases, only insects that do not affect animal or public health can be used.
- **THAILAND:** Thailand is pioneering Good Agricultural Practices (GAP) for cricket farming and is developing similar guidelines for BSF.
- **AUSTRALIA:** Insects may be used as feed for aquaculture and poultry, but there are restrictions on substrates, such as prohibiting manure or catering waste for feed purposes.
- **SUB-SAHARAN AFRICA:** While regulations are lacking in many countries, efforts are underway in Kenya and Uganda to draft regulations for insects as food and feed.
- **BRAZIL:** Although Brazil is the leading global exporter of poultry, the Brazilian feed law does not yet foresee insects to be permitted as animal feed.
- **USA:** Insects can be fed a very wide range of substrates if they are used for technical purposes (e.g., biodiesel, cosmetics) and not as feed or food.
- **EUROPEAN UNION:** The EU has stringent regulations, allowing insects to be reared only on specific substrates of vegetable or permitted animal origin. The 2017 EU regulation allowed BSF facilities to harvest and kill insects without requiring registration as a slaughterhouse.

INDUSTRY ENGAGEMENT

In many parts of the world, the insect industry is represented by international associations that act as intermediaries between the industry, academia, customers, and governments. These associations play a key role in supporting the development of legislative frameworks and advocating for sensible, industry-supportive regulations, and promoting the benefits of insect farming as a sustainable solution for food and feed production. They also facilitate knowledge exchange, provide technical guidance, and support the standardization of production practices, which are critical for building consumer trust and fostering market growth. In regions where regulatory frameworks are under development, engaging with these associations can provide operators with valuable support, helping them navigate complex legal landscapes and align their operations with emerging standards. Key organizations in this space include:

- **Asian Food and Feed Insect Association (AFFIA)**
- **Insect Protein Association of Australia (IPAA)**
- **North American Coalition for Insect Agriculture (NACIA)**
- **International Platform of Insects for Food and Feed (IPIFF)**

ENABLING ENVIRONMENT FOR BSF TECHNOLOGY

By implementing a legal framework that encourages innovation while ensuring safety and sustainability, governments can foster the growth of BSF technology in ways that benefit entrepreneurs, society, and the environment.

1. Clear and flexible feedstock regulations

- **Broad acceptance of organic waste:** A regulatory framework should allow the use of a wide variety of organic waste as feedstock for BSF larvae, including food scraps, agricultural by-products, and certain non-hazardous animal by-products. This flexibility reduces input costs and supports the circular economy by diverting waste from landfills.

- **Safety standards for feedstock:** Clear guidelines on acceptable levels of contaminants (e.g., heavy metals, pathogens) in feedstock would ensure that waste used in BSF systems is safe, minimizing health and environmental risks while allowing for more flexibility in sourcing.

- **Simplified approval processes:** Governments could create a fast-track process for approving new types of waste as feedstock, enabling operators to adapt quickly to changes in local waste availability.

2. Incentives for sustainable practices

- **Tax breaks and subsidies**: Governments should offer tax incentives, grants, or subsidies for BSF projects that contribute to waste reduction, recycling, or sustainable agriculture. This encourages businesses to adopt environmentally friendly technologies, making BSF operations more attractive financially.

- **Carbon credits and climate policies:** BSF technology helps reduce greenhouse gas emissions by diverting organic waste from landfills, where it would otherwise produce methane. Policies that allow BSF operators to earn carbon credits for emissions reduction would encourage the expansion of the industry and provide additional revenue streams.

3. Streamlined licensing and permitting

- **Simplified waste management licensing:** Many BSF operations involve processing organic waste, which typically requires a waste management license. The legal framework should streamline this process for small- and medium-scale operators, providing clear guidelines that reduce administrative burdens.

- **Flexible zoning laws:** Zoning regulations should be flexible enough to allow BSF operations in agricultural, industrial, and urban areas, if they meet environmental and safety standards. This would enable entrepreneurs to establish facilities close to waste sources, reducing transportation costs and carbon footprints.

4. Standards for insect-derived products

- **Uniform quality and safety standards:** Clear standards for BSF-derived products like protein meal, fat, and frass should be established. These standards would ensure product safety and quality, providing assurance to consumers and promoting wider market acceptance.

- **Recognition of BSF as feed:** The legal framework should explicitly recognize BSF protein meal as an acceptable animal feed ingredient, not just for aquaculture but also for poultry, pigs, and pets. This would open up new markets for BSF products and boost demand.

5. Research and innovation support

- **Funding for R&D:** Governments should fund research into improving BSF technology, such as optimizing feed conversion rates, enhancing product safety, and developing efficient production processes. Research grants or public-private partnerships can foster innovation and accelerate technology development.

- **Support for pilot projects:** Legal frameworks should allow pilot projects to operate with minimal bureaucratic obstacles, helping entrepreneurs test and scale their BSF technologies. Providing temporary exemptions from certain regulations (while ensuring safety) could stimulate innovation and reduce entry barriers.

6. Collaboration with industry and associations

- **Engagement with insect industry associations:** Governments should collaborate with insect industry associations, which represent the interests of BSF operators, researchers, and businesses. Involvement in shaping legislation helps create regulations that balance the needs of entrepreneurs, consumers, and the environment.

- **International harmonization of regulations:** Encouraging cross-border alignment of regulations on insect farming would open international markets for BSF products. Harmonized standards for product quality, processing, and safety would make it easier for BSF companies to export their products.

7. Education and awareness campaigns

- **Promoting public awareness:** Public campaigns highlighting the environmental and economic benefits of BSF technology can help build consumer trust in insect-based products. Government support for education initiatives could increase demand for insect-derived feed and fertilizers.

- **Training programs for farmers and entrepreneurs:** Offering training programs on how to integrate BSF technology into existing agricultural and waste management systems would encourage more people to adopt the technology and improve operational efficiency.

8. Regulations on animal welfare

- **Ethical treatment guidelines:** While research on insect sentience is still developing, clear guidelines on the ethical treatment of insects (e.g., humane killing methods) can be introduced to ensure that insect farming practices are responsible and sustainable. This will support societal acceptance and align with broader ethical concerns in food production.

Further reading:

- IPIFF (2023), IPIFF perspectives on the evolution of the European insect sector towards 2030: current EU regulatory status, existing opportunities and prospects for development
- IPIFF (2021a), Fact sheet on frass
- Lähteenmäki-Uutela et al. (2021), Regulations on insects as food and feed: a global comparison

ENVIRONMENTAL AND FOOD SAFETY ASPECTS

GREENHOUSE GAS EMISSIONS

The BSF technology presents compelling reasons for its potential to significantly reduce greenhouse gas (GHG) emissions, positioning it as an environmentally sustainable option for both waste management and protein production. The benefits of BSF lie in its ability to lower emissions during waste processing, promote circular economy practices, and lessen dependence on conventional protein sources.

1. Reduction of Methane Emissions from Landfills

- **Organic waste diversion:** One of the primary benefits of BSF larvae is their ability to rapidly consume and convert organic waste, diverting it from landfills. When organic waste is dumped in landfills, it decomposes anaerobically, producing significant amounts of methane (CH_4), a potent greenhouse gas. Every ton of food-waste that ends up in the landfill creates methane in an amount comparable to 930 kg of CO_2 equivalent (Scharff et al., 2023). On the other hand, BSF technology produces between 50 and 300 kg of CO_2 equivalent for the treatment of one ton of organic waste (Mertenat et al., 2019; Spykman et al., 2021). Major contributing factors are the energy use for pretreatment and processing (drying) of the product as well as the composting phase of the frass.

- **Efficient waste processing:** BSF larvae can reduce waste mass by up to 80% (wet weight), significantly decreasing the volume of waste that would otherwise contribute to methane production.

2. Lower Carbon Footprint Compared to Traditional Protein Sources

- **Alternative to fishmeal and soymeal:** Insect protein, such as that derived from BSF larvae, is a sustainable alternative to traditional animal feed ingredients like fishmeal and soymeal. The production of fishmeal involves industrial fishing, which depletes marine ecosystems and contributes to biodiversity loss. Soymeal production is associated with deforestation in regions like the Amazon, leading to substantial carbon emissions. By replacing these feed sources with BSF larvae, emissions related to deforestation, land use change, and overfishing are reduced.

- **Efficient feed conversion:** BSF larvae have a high feed conversion efficiency, meaning they can convert organic waste into protein with lower inputs (feed, water, energy) compared to livestock like chickens, pigs, or cattle. This results in a lower carbon footprint for producing protein.

3. Reduction of Nitrous Oxide Emissions

- **Alternative to traditional fertilizers:** The frass produced by BSF operations is rich in nutrients like nitrogen, phosphorus, and potassium (NPK) and can be used as an organic fertilizer. Using BSF frass as a fertilizer alternative to synthetic nitrogen fertilizers helps reduce nitrous oxide (N_2O) emissions, which are produced by synthetic fertilizers and are a powerful GHG.

4. Energy Efficiency in Waste Processing

- **Reduced energy demand:** Compared to some traditional waste management processes like incineration or high-energy composting, BSF larvae require less energy to process organic material. Particularly in tropical regions, BSF farming can operate with minimal energy inputs for climate control (e.g., HVAC systems), further reducing GHG emissions.

- Potential for heat recovery: In non-tropical regions where temperature control is needed, there is potential to integrate heat recovery systems to reduce energy consumption, thereby lowering emissions.

5. Circular Economy Contributions

- **Waste-to-resource transformation:** The BSF technology embodies the principles of the circular economy by converting organic waste into valuable resources like protein, oil, and fertilizer. This reduces the need for virgin resources, thereby lowering the overall emissions associated with sourcing, producing, and transporting alternative inputs (e.g., soymeal, chemical fertilizers).

- **Biogas potential from residual waste:** The residual waste from BSF processing can still be used for biogas production, capturing methane and converting it into energy. This helps reduce GHG emissions that would have been released during traditional waste decomposition.

6. Lower Transport Emissions

- **Local waste processing:** BSF facilities can often be set up near waste sources (e.g., food processing plants, urban centers), reducing the need to transport waste over long distances to landfills or incineration facilities. Shorter transport distances lower emissions from vehicles used in waste collection and management.

Efforts are underway to develop methods that can integrate black soldier fly (BSF) technology into the carbon credit market (including data measuring emission reductions through BSF technologies), and potentially Article 6 of the Paris Agreement, leveraging its investment potential to reduce greenhouse gas emissions. The idea is rooted in BSF's ability to divert organic waste from landfills, significantly lowering methane emissions, while converting waste into valuable products like protein and organic fertilizer. Researchers and industry experts are exploring ways to quantify these emissions reductions, aiming to create standardized methodologies that would allow BSF operations to generate carbon credits. This would provide an additional financial incentive for BSF businesses, enabling them to monetize their environmental benefits. The ongoing work focuses on validating these reductions, ensuring transparency in the carbon crediting process, and aligning with global carbon standards, thereby opening new revenue streams for BSF operators while supporting climate mitigation efforts.

PRODUCTION AND HYGIENE STANDARDS

As BSF farming is widely promoted as a waste management strategy, it presents both opportunities and challenges in terms of disease prevention, bioaccumulation, and food safety. While the BSF technology has the potential to reduce waste and create sustainable feed alternatives, careful attention must be given to the potential risks associated with pathogens, contaminants, and toxins present in the feedstock. Strict regulatory frameworks are essential to ensure that insect-derived products meet the highest standards of hygiene and safety, preventing cross-contamination and safeguarding public health. Understanding these risks and implementing stringent controls are critical for the long-term success and trust in BSF technology.

1. Disease Prevention and Contamination Control

- **Pathogen Risks:** Organic waste, particularly from food and animal by-products, can contain harmful pathogens such as Salmonella, *E. coli*, and viruses. If these pathogens are not properly eliminated through controlled feed substrates or processing of insects, they could be passed on to the larvae and eventually to livestock or humans, posing serious health risks.

- **Cross-Contamination:** Feeding insects with waste that includes animal by-products (e.g., slaughterhouse waste) or manure raises the risk of cross-contamination between species. Strict controls ensure that harmful bacteria, prions, or other contaminants are not introduced into the food chain through insects.

2. Bioaccumulation of Toxins

- **Heavy Metals and Chemicals:** Organic waste from certain sources may contain contaminants such as heavy metals, pesticides, or other hazardous chemicals. BSF larvae could accumulate these substances, and if the larvae are fed to animals or used in human food, it could lead to bioaccumulation, potentially causing health issues further up the food chain. It is therefore necessary to regularly check the composition of the substrates and products.

3. Food Safety Standards

- **Regulatory Consistency:** Insects used for animal or human consumption must adhere to the same food safety standards as traditional feed or food products. This ensures that the quality and safety of all products in the food chain, whether they come from insects or conventional sources, meets stringent hygiene, processing, and handling requirements.

- **Consumer Confidence:** Strict regulations are also designed to protect consumer confidence in new food technologies, like using insects for animal feed or human food. Ensuring that insects are fed safe, controlled substrates and processed correctly helps avoid public health scares and builds trust in insect-based products.

4. Prevention of Zoonotic Diseases

- **Animal-Origin Feed Risks:** Feeding animals or insects waste products from other animals, particularly untreated or raw animal products, has historically led to the spread of zoonotic diseases. For instance, the bovine spongiform encephalopathy (BSE) crisis (mad cow disease) was caused by feeding cattle with contaminated animal protein. To prevent similar risks, many countries strictly regulate the use of animal waste in insect and livestock feed.

5. Environmental Impact

- **Waste Management:** Allowing unrestricted use of waste in insect farming could lead to improper waste handling, resulting in environmental degradation. Strict rules ensure that waste is safely processed, reducing harmful environmental impacts such as contamination of water supplies or soil.

The combination of waste management and feed production requires adherence to clear and rigorous hygiene protocols. In general, however, the safety of products, consumers, and staff can be ensured by the physical separation of areas and the adherence to Hazard Analysis and Critical Control Point (HACCP) protocols. IPIFF Guide on Good Hygiene Practices for EU producers of insects as food and feed (IPIFF, 2024) equalizes the requirements regarding personal protective equipment (PPE) in the insect industry with those in food production facilities.

Further reading:

- IPIFF (2024), Guide on Good Hygiene Practices for European Union (EU) producers of insects as food and feed
- NACIA (2024), Best Practices - Commercial Insect Production
- Parodi et al. (2022), Principles for the responsible use of farmed insects as livestock feed

ETHICAL AND SOCIAL DIMENSIONS OF BSF SYSTEMS

ETHICAL CONSIDERATIONS

To assess BSF welfare, one often applies the Five Freedoms model, initially developed to address the concerns over intensive agricultural systems, and which over time has been adapted to encompass broader aspects of animal welfare. This adapted model continues to guide ethical treatment, emphasizing the need to ensure not just survival, but also quality of life for animals – the Five Domains model. The five domains are:

1. **Freedom from hunger and thirst**
   Insects should have access to proper nutrition and hydration.
2. **Freedom from discomfort**
   Their living environment should be appropriate, providing suitable shelter and conditions.
3. **Freedom from pain, injury, and disease**
   Insects should be protected from harm, ensuring humane treatment and handling.
4. **Freedom to express normal behavior**
   Insects should be allowed to exhibit natural behaviors, such as movement and social interaction, where applicable.
5. **Freedom from fear and distress**
   Their environment and management should minimize stress and anxiety.

These freedoms help guide ethical practices in insect farming, aiming to ensure humane treatment at every stage of production. One critical aspect of the BSF technology is the killing step. Currently, there is no data or regulations on humane slaughter methods for BSF larvae. Based on time-to-death, the most humane methods are likely boiling/blanching, freezing in liquid nitrogen, and grinding, as these cause near-instantaneous death. Less humane methods include sand roasting, microwaving, sun baking, oven baking, and freezing in air, all of which result in slower death and likely cause more pain. Asphyxiation (deprivation of oxygen) is also considered inhumane due to its slow, drawn-out process. The use of anesthetics prior to slaughter could improve welfare, but more research is needed to confirm this (Barrett et al., 2022).

Another area that affects the welfare of the animals themselves, but also the future of BSF technology, is the manipulation of genetic material and the creation of genetically modified breeding lines. Genetic modification of BSF, often using CRISPR/Cas9 technology, could have significant effects on their welfare and industrial use. Current developments include:

1. **Extending the larval stage**
   Disabling the *Ptth* gene has resulted in a twofold to threefold increase in body weight. This modification enhances their feeding capacity and larval size.
2. **Boosting nutrient content**
   Another focus is increasing specific nutrients in the larvae to create optimal nutritional profiles for human consumption, though details are limited.
3. **Creating flightless adults**
   By silencing the *Vg* gene, researchers are working on flightless adults, which can be housed in smaller cages. This gene controls wing size and shape.

Modifications 1 and 3 raise concerns about BSF welfare. Flightless adults could lose the ability to express normal behavior, and extended larval feeding and larger body sizes might negatively affect health and restrict normal behavior, though no data on larval behavior under the *Ptth* modification is available yet (Barrett et al., 2022).

As the BSF sector rapidly develops, it is important not to lose sight of ethical principles, which have now become the norm in conventional animal husbandry. These principles apply not only to the conditions of animal husbandry itself, but also, for example, to the processing of the harvested animals into biodiesel or soap.

ECONOMIC EMPOWERMENT

To ensure that enterprises embrace new business models , value must be created for enterprises, clients, and society as a whole (Osterwalder & Pigneur, 2010). As businesses are not non-profit, they must generate profit, not lose money without neglecting the social and environmental pillars of sustainability. The products that they release to the market must be feasible as well as profitable (Madau et al., 2020).

BSF technology offers opportunities for job creation, particularly in waste management, farming, and processing industries. In regions where BSF operations are integrated into smallholder farming or community-based models, the technology can empower local populations, particularly women, by providing a source of income through sustainable waste management and protein production.

However, concerns about labor practices arise, especially in large-scale industrial BSF operations. The work involved in reproduction, harvesting, and processing can be labor intensive, and in countries with low labor costs, this may lead to the exploitation of workers if proper labor standards are not upheld. It is important for companies to implement fair labor practices, including safe working conditions, fair wages, and adequate training, to ensure ethical labor practices throughout the supply chain.

The Women Income Network (WIN) in Uganda has launched a contract farming model to help women start maggot farming by providing infrastructure, seed stock, and waste mobilization support. Farmers repay WIN based on income from their operations, making the model sustainable and scalable. This approach empowers women economically, promotes environmental sustainability through waste management, and fosters community development by reinvesting repayments to support more beneficiaries.

CASE SNAPSHOT | **Contract farming**

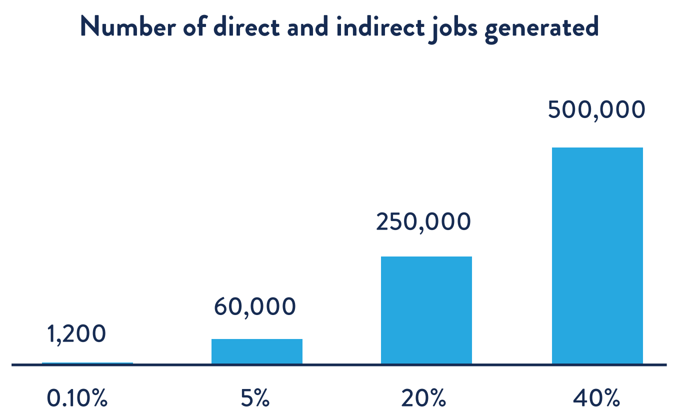
An NGO in Uganda empowers women and youth through a contract farming model centered around black soldier fly production. The NGO funds and provides technical support for BSF infrastructure and collaborates with the town council to source biowaste, delivered by a contractor. Farmers receive biowaste and starter larvae, rear the larvae, and then sell them back at a fair price, with partial payment retained for investment repayment. The larvae are sold to local poultry farmers for 3,000 UGX/kg (0.75 USD/kg) and the frass is sold for 650 UGX/kg (0.16 USD/kg). The revenue breakdown shows that the frass is the leading product, generating the same revenue as fresh larvae and dried larvae together.

SOCIO-ECONOMIC OUTREACH

In Kenya, assuming a replacement of fishmeal, maize, and soy bean meal in the ranges of 5–15% by up to 50% of the poultry sector, each ton of the biowaste treated with BSF could generate USD 66 to the Kenyan economy, which is nearly threefold higher than the cost of waste disposal in Nairobi (Abro et al., 2020). At the same time, it creates 25,000–76,000 additional jobs. Factors which lead to this effect are, for example, increased food security and savings through the avoidance of imports. Abro et al. (2022) calculated the job creation potential for Uganda when conventional feed is being replaced by insect-based feed and concluded that each percent replaced creates 12,500 new jobs (Figure 6).

FIGURE 6

Number of jobs created in uganda at different rates of replacement of feed with insect based feed



In the case of labor-intensive plants in sub-Saharan Africa or South-East Asia, one can roughly assume one worker per ton of waste per day. For example, for a small city like Hawassa, Ethiopia, with a population of about 500,000 that generates about 50 tons of organic waste per day (JICA, 2022), this means that BSF can employ some 50 people.

CASE SNAPSHOT **Mini-livestock for smallholder farmers**

Small-scale farmers in Malawi convert waste such as pig manure or crop residues into larvae. They follow a simple feeding plan that allows them to operate BSF production in a way that is comparable to beekeeping in terms of the time required. The larvae needed for operations are supplied by a local NGO or produced by a village-based cooperative. The buckets/trays and tools (spoons, spade) for the handling of the substrate for a set-up which can handle around 10 kg of substrate per week costs 15-20 USD as an investment. The approx. 2.5 kg of fresh larvae can be fed directly to chickens or pigs and replace feed worth ~1.5 USD. Since the farmers started feeding their livestock larvae, they've observed significant improvements. Chickens are growing faster, allowing them to reach optimal selling size in just 5 weeks instead of the usual 6. For those raising layers, egg sizes have also increased. This accelerated growth applies to pigs as well.

Empowering smallholder farmers to become self-sufficient in producing their own feed and fertilizer can foster a local circular economy, where rural communities actively participate in a profitable economic value chain with strong returns on investment. Such rural development is vital to increase the resilience of vulnerable households but also for the support of the peace process in post-war situations as it can become an important driver of reintegration of ex-combatants by providing access to the local economy (Barragán Fonseca et al., 2020).

Further reading:

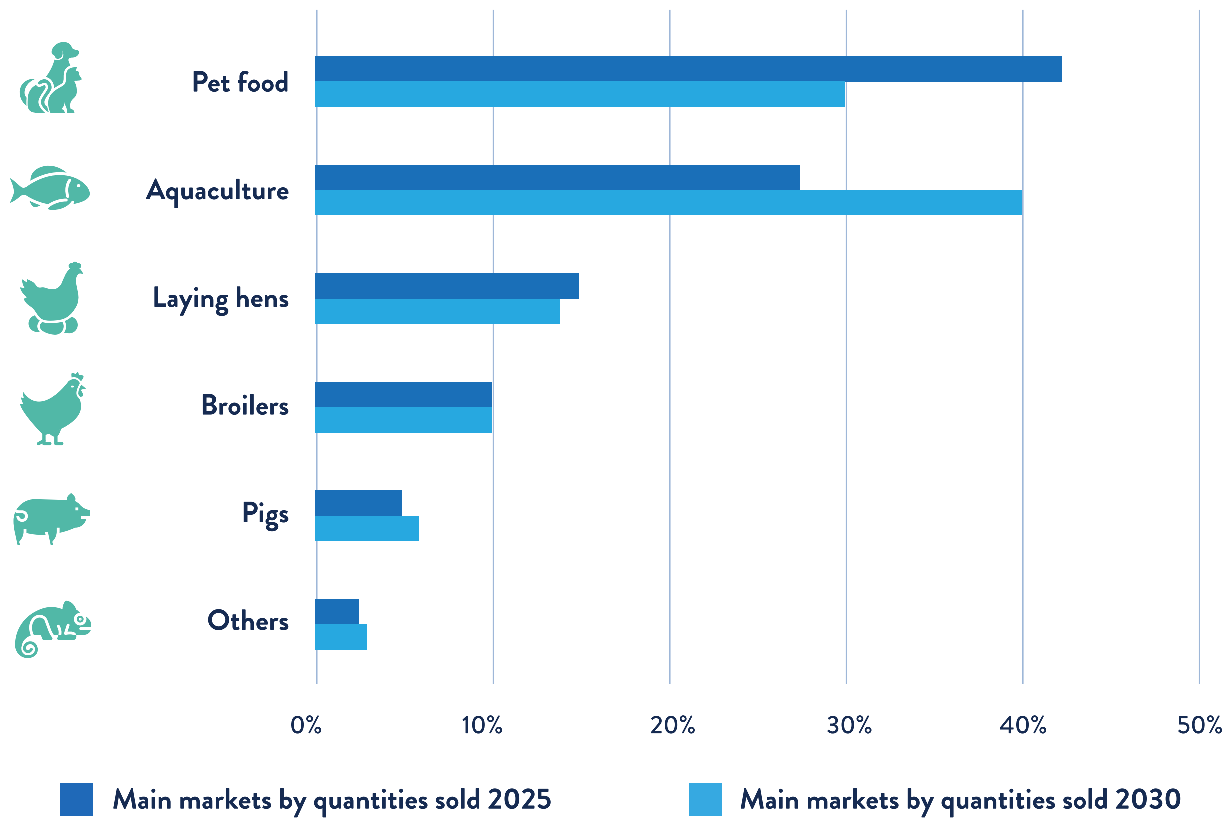
- Barrett and Adcock (2023), Animal welfare science: an integral piece of sustainable insect agriculture
- Arndt et al. (2024), Near and Dear? If animal welfare concepts do not apply to species at a great phylogenetic distance from humans, what concepts might serve as alternatives?

MARKET OPPORTUNITIES AND BARRIERS

The global market for BSF technology is diverse and dynamic, with significant growth potential across sectors like aquafeed, livestock feed, pet food, soil fertility and waste management. Growing opportunities lie in regions with a supportive regulatory environment, established aquaculture industries, and strong sustainability incentives. However, challenges related to regulation, feedstock availability, and infrastructure vary regionally, influencing how quickly BSF can scale and meet demand in different markets.

In the EU, businesses mainly focus on the pet food market. While only 3% of all feed produced is for pets, 50% of the large insect industry is engaged in producing for this sector (Siddiqui et al., 2024). But the sector faces changes in the near future. Following the approval of EU Regulation 2017/893, which authorised the use of processed animal proteins dervied from farmed insects (insect PAPs) in aquaculture feed, aquafeed has become increasingly important and will most likely be the focus in the future for European insect producers (Figure 7). The International Platform of Insects for Food and Feed (IPIFF) estimates that by 2030, more than 5% of the fish consumed in the EU will be derived from fish farms that use insect protein in their aquafeed formulations and about 1% of the chicken meat servings consumed in the EU will be derived from insect-fed broilers, especially with recent discussions on authorizing insect PAPs for poultry and pig feed.

FIGURE 7 Projected breakdown of the european market for insect protein (in percent), IPIFF 2021



The global BSF market 2019 had a value of USD 128 million but is expected to increase to USD 3.4 billion by 2030 (Siddiqui et al., 2024). KPMG estimates the market for insect-based animal food to EUR 250 million in 2023 and expects it to reach EUR 650 million by 2030 (KPMG, 2024). In 2019, Asia Pacific held the greatest share of the global market in terms of volume (57.1%) and value (almost 50%). The reasons for this dominance could be the more flexible legislation, the favorable climate, and the lower wages in this region.

But there are market opportunities for smaller-scale operations as well. A market study by Eawag on the demand for BSF products in the Indonesian city of Surabaya showed that the greatest potential lies in the sale of products for ornamental birds and fish.

Even if the market potential of 1 million USD/month is small compared to 70 million on the feed market, the barrier to entry to the market is considerably lower and the prospect of rapid success is greatly increased. Dried larvae reached a price of USD 25/kg when sold on the market for domesticated animals while BSF meal could be sold for USD 0.55/kg as feed for farmed animals (Antarest et al., 2020). In Kenya, dried larvae are sold at an average price of USD 0.95 and in Uganda for USD 1.15 (Meerts et al., 2023).

In most cases, however, BSF will have to compete with established products. Figure 8 shows the price range of BSF meal in different world regions compared to the global fish and soybean meal price.

FIGURE 8

Comparison of prices for BSF meal in different regions of the world (Transparency Market Research, 2020)

A work package of the European Horizon 2020 project SUStainable INsect CHAIN (SUSINCHAIN) developed eight different scenarios for the European insect market.

- ### Sustainability and innovation

  In scenarios where strong environmental policies and sustainability goals are prioritized, the insect farming industry benefits from high consumer acceptance, government support, and innovation. Such environments encourage growth in alternative protein sources. The integration of research, advisory systems, and public-private collaboration creates dynamic ecosystems where small- and medium-sized enterprises (SMEs) can thrive.

- ### Economic resilience

  Scenarios that emphasize food security and self-sufficiency provide stability for the insect farming sector, ensuring strong domestic markets for insect-based products. Favorable financial conditions, such as access to public and private credit, help both large companies and SMEs scale up operations.

- ### Global sustainability standards

  The implementation of global environmental regulations or economic policies focused on sustainability could drive the demand for insect-based proteins. This would create a market where alternative proteins are promoted through pricing structures that penalize unsustainable products, further advancing insect farming and helping it compete with traditional protein sources.

- ### Regulatory overload

  In scenarios where strict regulations are enforced to ensure sustainability, safety, and transparency, the regulatory burden can become a barrier to growth. High compliance costs and complex regulations can stifle innovation and make it difficult for smaller companies to compete, leading to market dominance by larger corporations. This can limit market diversity and create a rigid industry structure.

- ### Market consolidation

  In competitive, profit-driven environments, insect farming becomes dominated by large companies. These markets focus on cost reduction and profit maximization, often sidelining environmental or ethical concerns. In such contexts, SMEs either struggle to survive or are absorbed by larger corporations, reducing opportunities for small-scale operators and limiting consumer choice in insect-based products.

- ### Outsourcing and quality concerns

  In scenarios where insect production is outsourced to other regions, the domestic insect farming industry weakens. Lack of investment and support for local producers leads to reliance on imports, which raises concerns about product safety, transparency, and traceability. This reliance on external sources undermines the potential for building a robust, sustainable insect farming ecosystem within the local economy.

- ### Fragmented regulation

  When countries or regions adopt independent agricultural and food policies, the insect farming industry becomes fragmented, with inconsistent standards for sustainability and safety. This patchwork approach makes it difficult for the sector to grow cohesively, and countries with fewer resources struggle to build competitive insect farming industries, leading to uneven development across regions.

In summary, the most favorable outcomes for insect farming occur in environments where sustainability, innovation, and collaboration are prioritized, while challenges arise from regulatory burdens, market consolidation, outsourcing, and fragmented regulations. Balancing these factors is crucial for fostering a thriving and resilient insect farming sector.

Further reading:

- Gambelli et al. (2022), Report on Future Market Opportunities for Commercialization and Acceptance of Insects as Ingredients by Food Chain Actors
- IPIFF (2021b), An overview of the European market of insects as feed

OUTLOOK: THE FUTURE OF BSF TECHNOLOGY

The future of the black soldier fly technology is marked by both promising opportunities and critical challenges. As the industry continues to scale, its role in sustainable food systems, waste management, and circular economy models is expected to deepen. Technological innovations, particularly in automation, genetic optimization, and feedstock diversification, will drive greater efficiency and productivity across both large-scale industrial operations and decentralized, smallholder setups.

Regulatory frameworks will play a decisive role in shaping the trajectory of the BSF sector. While existing regulations are often fragmented, there is a growing trend toward harmonizing standards, especially concerning food and feed safety, environmental impact, and waste management. This alignment will help unlock new markets and facilitate cross-border trade of insect-based products.

A key emerging topic is animal welfare in insect farming, an area previously overlooked but gaining attention as the industry matures. Discussions around humane slaughter methods, ethical farming practices, and potential welfare standards for BSF are likely to influence future regulatory landscapes. As ethical considerations become more prominent, the industry may need to adapt operational models to align with evolving societal expectations regarding animal welfare, even for insects.

Moreover, the potential integration of BSF operations into carbon credit schemes could open new revenue streams, enhancing the economic sustainability of the sector. By positioning BSF technology at the intersection of environmental sustainability, economic opportunity, and ethical responsibility, the industry can solidify its role as a transformative force in global food and waste systems.

BIBLIOGRAPHY

Abro, Z., Berresaw, M., Tanga, C., Beesigamukama, D., Diiro, G. 2020. Socio-economic and environmental implications of replacing conventional poultry feed with insect-based feed in Kenya. **Journal of Cleaner Production**, **265**, 121871.

Abro, Z., Macharia, I., Mulungu, K., Subramanian, S., Tanga, C., Berresaw, M. 2022. The potential economic benefits of insect-based feed in Uganda. Frontiers in **Insect Science**, **2**.

Antarest, E., Egger, J., Virard, G., Dortmans, B., Zurbrügg, C. 2020. Market assessment for BSF products. Eawag.

Arndt, S.S., van der Staay, F.J., Goerlich, V.C. 2024. Near and Dear? If animal welfare concepts do not apply to species at a great phylogenetic distance from humans, what concepts might serve as alternatives? **Animal Welfare**, **33**, e38.

Badeski, M. 2023. Investment Insights for the Insect Industry - Perspectives from an exited founder.

Barragán Fonseca, K., Barragán-Fonseca, K., Verschoor, G., van Loon, J., Dicke, M. 2020. Insects for peace. **Current Opinion in Insect Science**, **40**.

Barrett, M., Adcock, S.J.J. 2023. Animal welfare science: an integral piece of sustainable insect agriculture. **Journal of Insects as Food and Feed**, **10**, 1-15.

Barrett, M., Chia, S.Y., Fischer, B., Tomberlin, J. 2022. Welfare considerations for farming black soldier flies, Hermetia illucens (Diptera: Stratiomyidae): a model for the insects as food and feed industry. **Journal of Insects as Food and Feed**, **9**, 1-30.

Diener, S., Gold, M. 2022. Global study on black soldier fly sector. Subnational Climate Fund.

Dortmans, B., Egger, J., Diener, S., Zurbrügg, C. 2021. **Black Soldier Fly Biowaste Processing - A Step-by-Step Guide**. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Fantechi, T., Califano, G., Caracciolo, F., Contini, C. 2023. Puppy Power: How Neophobia, Attitude towards Sustainability, and Animal Empathy Affect the Demand for Insect-Based Pet Food. **Food Research International**, **177**, 113879.

Gambelli, D., Vairo, D., Zanoli, R. 2022. Report on Future Market Opportunities for Commercialisation and Acceptance of Insects as Ingredients by Food Chain Actors.

Hoang, V., Nguyen, M.-H. 2024. Organic wastes, black-soldier flies, and environmental problems through the lens of the stock market.

IPIFF. 2021a. Fact sheet on insect frass.

IPIFF. 2021b. An overview of the European market of insects as feed.

IPIFF. 2023. IPIFF perspectives on the evolution of the European insect sector towards 2030: current EU regulatory status, existing opportunities and prospects for development.

IPIFF. 2024. Guide on Good Hygiene Practices for European Union (EU) producers of insects as food and feed.

JICA. 2022. Data collection survey on municipal solid waste management in African cities. Japan International Cooperation Agency.

Jong, B.d., Nikolik, G. 2021. No longer crawling: Insect Protein to Come of Age in the 2020s. Rabobank.

KPMG. 2024. Alternative Protein Deal Cosmos.

Lähteenmäki-Uutela, A., Marimuthu, S.B., Meijer, N. 2021. Regulations on insects as food and feed: a global comparison.

Journal of Insects as Food and Feed, **7**(5), 849-856.

Madau, F.A., Arru, B., Furesi, R., Pulina, P. 2020. Insect Farming for Feed and Food Production from a Circular Business Model Perspective. **Sustainability**, **12**, 5418.

Meerts, A., Martinussen, L., Kizito Muganga, A. 2023. Mapping of the Black Soldier Fly value chain in East Africa. FAO.

Mertenat, A., Diener, S., Zurbrügg, C. 2019. Black Soldier Fly biowaste treatment – Assessment of global warming potential. **Waste Management**, **84**, 173-181.

Mouhrim, N., Peguero, D., Green, A., Silva, B., Anita, A., Ristić, D., Tonda, A., Mathys, A., Smetana, S. 2023. Optimization models for sustainable insect production chains. **Journal of Insects as Food and Feed**, **10**, 1-19.

Mutuku, K.V., Mukhebi, A.W., Orinda, M.A., Tanga, C.M. 2022. Determinants of profitability of black soldier fly farming enterprise in Kenya. **Journal of Insects as Food and Feed**, **8**(6), 693-700.

NACIA. 2024. Best Practices - Commercial Insect Production.

Osterwalder, A., Pigneur, Y. 2010. **Business Model Generation - A Handbook for Visionarie, Game Changers, and Challengers.** Wiley.

Parodi, A., Ipema, A.F., Van Zanten, H.H.E., Bolhuis, J.E., Van Loon, J.J.A., De Boer, I.J.M. 2022. Principles for the responsible use of farmed insects as livestock feed. **Nature Food.**

Scharff, H., Soon, H.Y., Rwabwehare Taremwa, S., Zegers, D., Dick, B., Villas Boas Zanon, T., Shamrock, J. 2023. The impact of landfill management approaches on methane emissions. **Waste Manag Res**, 734242X231200742.

Siddiqui, S., Brunner, T., Tamm, I., Read, P., Patekar, G., Bahmid, N., Aarts, K., Paul, A. 2022. Insect-based dog and cat food: A short investigative review on market, claims and consumer perception. **Journal of Asia-Pacific Entomology**, 102020.

Siddiqui, S., Gadge, A., Hasan, M., Rahayu, T., Nikolaevich, P., Fernando, I., Castro-Muñoz, R. 2024. Future opportunities for products derived from black soldier fly (BSF) treatment as animal feed and fertilizer - A systematic review. **Environment Development and Sustainability**.

Spykman, R., Hossaini, S.M., Peguero, D.A., Green, A., Heinz, V., Smetana, S. 2021. A modular environmental and economic assessment applied to the production of Hermetia illucens larvae as a protein source for food and feed. **The International Journal of Life Cycle Assessment**, **26**(10), 1959-1976.

van Huis, A. 2022. Edible insects: Challenges and prospects. **Entomological Research**, **52**(4), 161-177.

Yang-Jie, D., Xiang, F.M., Tao, X.H., Jiang, C.L., Zhang, T.Z., Zhang, Z.J. 2023. A full-scale black soldier fly larvae (Hermetia illucens) bioconversion system for domestic biodegradable wastes to resource. **Waste Manag Res**, **41**(1), 143-154.

ABOUT THE CCAC

The UNEP-convened Climate and Clean Air Coalition (CCAC) is a voluntary partnership of more than 190 stakeholders including more than 91 country partners seeking to reduce methane and other super pollutants to limit global warming to 1.5°C. Through its Trust Fund, the CCAC supports countries to reduce super pollutants emissions across sectors by 2030, while advocating for elevated ambition and advancing the latest in policy-relevant science. Different funding windows exist, including for institutional strengthening, national planning, policies and regulation as well as sectoral transformation.

Following a decade of success in raising global methane ambition, the CCAC Secretariat is also providing secretariat functions to the Global Methane Pledge (GMP), a voluntary commitment of more than 150 countries to reduce global methane emissions by at least 30% by 2030 compared to 2020 levels.

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