SUBNATIONAL CLIMATE FUND

Global study on black soldier fly sector

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Acknowledgements

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Outline

Background and scope

Waste processing by black soldier fly (BSF) larvae is a promising organic waste treatment technology, due to the high waste reduction potential while producing marketable high-value products. Young BSF larvae are placed on organic waste where they feed for about one to two weeks, reducing the biomass by up to 70%. The grown larvae are harvested and sold as a component of animal feed for fish and poultry or pet food, and the residue remaining from the larval feeding process is a valuable soil conditioner or fertilizer. Less conventional markets for BSF-based products are biofuel, the cosmetic industry, pharmaceutical, and biotechnological. Entrepreneurs operating BSF facilities thus have the potential for creating inclusive business models, fostering job creation, and contributing to a circular economy.

R20 contacted Eclose to prepare an overview of the BSF technology, the existing players, and the dynamics in the global sector. The report should inform the Subnational Climate Fund initiative (SCF), which is implementing a blended-finance investment fund to invest in mid-sized infrastructure that aims at reducing greenhouse gas emissions and meeting other sustainable development goals. The study will help the SCF make investment decisions in the BSF sector, thus the readers of this study will be the consortium members of the SCF: R20, IUCN, Pegasus Capital Advisors, and Gold Standard, and its anchor investor, the Green Climate Fund. The information in the report will thus be used only internally by the above-mentioned partners.

Eclose and R20 agreed on the following objectives of the report. To complete the job in a timely manner and with the highest quality, Eclose joined forces with Gold Advisory for this mandate.

Objective 1: Overview of the BSF market

Objective 2: Overview of technical matters related to the operation of a BSF facility

Objective 3: Overview of the regulatory framework and respective regulatory trends

Objective 4: List environmental and social impacts of using BSF for organic waste treatment

This report is the summary off all findings derived from the scope of work.

Executive summary

The black soldier fly (BSF), *Hermetia illucens*, is a tropical fly used for the bioconversion of biowastes and byproducts into marketable, high-value products. The last decades have seen the engineering of the natural fly life cycle into commercial facilities. These facilities can range from basic and completely manual smallholder on-farm facilities processing a few hundred tons of feedstock per year to 50,000 m^2 completely automized and climatized facilities processing 70,000 tons of feedstock per year. Particularly the larger facilities need to be designed and implemented following a rigorous engineering process according to the available feedstock, product type, and market. Fortunately, in the last few years, many more technology and service providers have entered the market that can support in this endeavor. At the time of writing, this report mapped 121 BSF companies worldwide. Business models are based on smallholder farming, the production of high-quality ingredients for the pet and livestock markets (e.g., poultry, pig, aquaculture), waste management, genetics and sale of young larvae offspring, or the production of higher value products. Currently, the pet and livestock markets are the largest offtakes of larval products, which are used live, frozen, dried, as protein meal, or as fat in the diets of pets and livestock. More recently, more high-value products from chitin, fat, and melanin are also being investigated for use in technical, pharmaceutical, and cosmetics markets. Frass can be used as is, composted, used for biogas production, pyrolysis, or incinerated as fuel, or further refined into a fertilizer.

Investment banks and BSF companies have made positive projections about the market size and product prices from BSF facilities. However, these need to be considered with caution as they are not always backed by robust data and consider certain assumptions of the feedstock market and legislative landscape that may not materialize. The BSF sector operates and grows not in a void but is part of competitive and price-sensitive agri-food markets. For example, BSF companies compete with livestock farmers or biogas/biofuel companies for feedstock. Demand and supply of byproducts/wastes can change with livestock feed and gas prices. Regarding larval product, in terms of price and quality, BSF companies have to compete with the established, highly efficient and price-sensitive soybean and fishmeal value chains. Yet, by replacing these inputs, BSF facilities can contribute to food security and foreign currency savings.

Today, BSF facilities are established for the use of homogenous, high-value agri-food products as they deliver high larval rearing performance metrics, reliable product and meet the highest legal standard. However, they often come at a cost, have competing uses, and may not reduce the environmental impact in comparison to the status quo. In order to scale and make a dent on the global food and feed system, heterogenous feedstocks such as food waste or manures partially including inorganic materials need to be increasingly considered. They are more challenging regarding operation, product quality, legislation, and food safety, but they are in abundant supply and have the potential to deliver on some of the social and environmental benefits the sector desires.

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- Work experience and network in Africa, North America, Asia, Australasia, and Europe

Abbreviations and definitions

BSF: Black soldier fly, *Hermetia illucens*.

Breeding: The breeding contains the entire reproductive BSF life cycle. Young larvae are reared to prepupal stage. Prepupae are left to populate and flies are kept in cages.

Biowaste: Decaying material made up of various amounts of organic waste (e.g., food waste, manure, kitchen and household waste).

Byproduct: An organic material that is typically homogenous, has a favorable composition for resource recovery, and therefore already has a market value (e.g., as animal feed or for biogas, composting). Examples include brewers' spent grain, okara, potato peels, and palm kernel meal.

Bioconversion rate: Ratio of larval biomass and feedstock input.

Feedstock: Byproduct waste fed to BSF larvae.

Frass: The leftovers of BSF larvae bioconversion. This substance can be a crumbly, soil-like substrate or a wet slurry. It typically requires subsequent composting steps to stabilize before it can be used as solid amendment and/or fertilizer.

HVAC: Heating, ventilation, air conditioning. Typical part of a BSF facility in temperate climates to maintain a warm environment for BSF.

Nursery: Nurses the larvae for the first days of their lives on high-nutritious feedstock until they are large enough to be counted and resistant enough to be reared on more heterogenous byproducts and wastes.

Neonates: Larvae that just hatched from the BSF eggs.

Rearing: Rearing describes the growing of BSF larvae from 5DOL to harvest.

Ton: All units in the report are in metric units. 1 ton is 1,000 kg.

5DOL: Five-day-old larvae. Larvae following five days of hatching are frequently used for bioconversion of biowastes and byproducts because they are more resilient than neonates and can more easily be counted and dosed.

Description of the BSF technology

This section describes the natural life cycle of the black soldier fly (BSF), *Hermetia illucens*, and how it was engineered for waste treatment and production of high-value marketable products. The section also describes the different units of a BSF facility in detail. This section is mainly based on the authors' knowledge, Dortmans et al. (2021), Gold et al. (2018), Veldkamp et al. (2021), Van Huis & Tomberlin (2016), and other key literature cited across the section.

The natural life cycle

Figure 1 shows the natural BSF life cycle. *H. illucens* is of the dipteran family Stratiomyidae. It can be encountered in nature worldwide in the tropical and sub-tropical areas between the latitudes of 40°S and 45°N (Rozkosny, 1982; Üstüner et al., 2003). The adult BSF lives only around five to eight days and only feeds on liquid and no solid food during this time. Under suitable environmental conditions (mainly temperature, relative humidity, and light quantity and quality), a fertile female and male BSF can mate. The female BSF then lays an egg package of around 300-800 eggs into a dry place of small and sheltered cavities. This process is called oviposition and the female is attracted to the oviposition location by decaying biowaste (Bertinetti et al., 2019; Bogdan et al., 2022). The closeness of the eggs to the decomposing organic matter ensures that the larvae have their first food source nearby after hatching. The sheltered cavities protect the eggs from predators and prevent dehydration of the egg packages by direct sunlight. On average, the eggs hatch after two to four days and the emerged larvae, which are barely visible, will search for food and start feeding on the organic material nearby. The larvae feed voraciously on the decomposing organic matter and grow from less than one millimeter to around 2.5 cm length and 0.5 cm width and are of cream-like color.

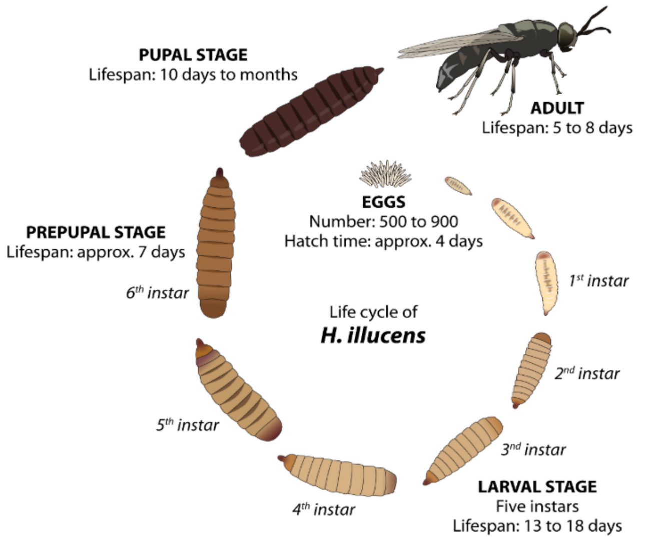


FIGURE 1: *THE NATURAL LIFE CYCLE OF THE BLACK SOLDIER FLY* (BSF), *HERMETIA ILLUCENS* (DE SMET ET AL., 2018).

Under optimal conditions with ideal food quality and quantity and temperatures around 28-32°C, the growth of the larvae will require a period of 13-18 days (Holmes et al., 2017; Li et al., 2016). However, BSF larva are particularly resilient organisms and have the ability to extend the life cycle under unfavorable conditions. The larval stage is the only stage during which the BSF larvae feed and, therefore, it is during this time of larval development that enough fat reserves and protein are stored to allow the larvae to undergo pupation, emerge as flies, find mates, copulate, and (as a female) lay eggs before dying.

After having gone through five larval stages, the larvae reach the final larval stage: the prepupa. When transforming into a prepupa, the larva replaces its mouthpart with a hook-shaped structure and becomes dark brown to charcoal grey in color. It uses this hook to easily move out and away from the food source towards a nearby dry, humus-like, shaded, and protected environment that it deems safe from predators, and this is where the fly emerges from the pupa and flies off without significant hindrance. The cycle starts again when the male and female find a suitable partner, mate, and eggs are oviposited (Giunti et al., 2018; Tomberlin & Sheppard, 2002).

Process units of an engineered BSF facility

BSF facilities accelerate and control the described natural life cycle of BSF to treat waste and produce marketable products (see sections "Established products" and "Alternative and emerging products"). As shown in Figure 2, a BSF facility can broadly be separated into six different units: 1) Feedstock preparation, 2) Dosing/loading and rearing (young larval offspring to harvest), 3) Breeding with nursery, 4) Product harvesting, 5) Post-processing of larvae and frass, storage, and outgoing logistics, and 6) Auxiliary processes (e.g., cooling, heating, pressurized air, air cleaning), offices, ablution, and laboratory. Below, these different units are described in detail. Feedstock sourcing and product marketing may also be inside the scope of a BSF company.

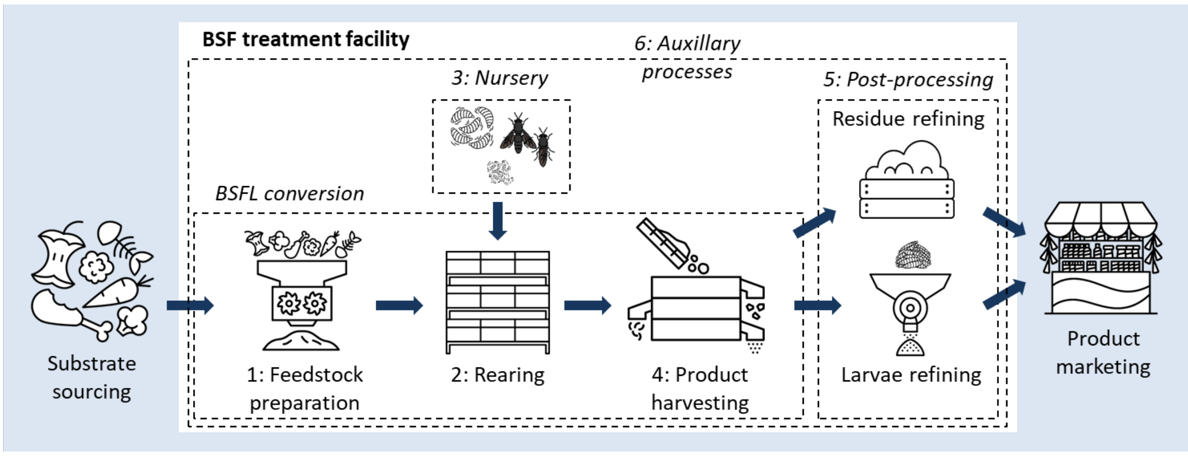


FIGURE 2: THE DIFFERENT UNITS OF A BSF FACILITY (DORTMANS ET AL., 2021).

Typically, all units are enclosed in one or several buildings. In temperate climates, this is typically one fully enclosed building with sections climatized with an HVAC system (heating, ventilation, air conditioning; i.e., for rearing, breeding;—see Better Insect Solutions or Bühler Group) (Figure 3). One building also has the advantage of improved control of other organisms (e.g., pathogens, parasites) entering the facility and BSF leaving the facility. This is relevant in countries where the release of BSF is legally restricted (e.g., Switzerland) (Swiss Federal

Council, 2012). In addition, emissions from the operation which are significant (similar to farming of other livestock, e.g., ammonia) and need to be regulated can be better treated if captured at source. Loads and concentrations of gaseous emissions depend on the feedstock, treatment operation (e.g., NH_3 releases from residue at alkaline pH), HVAC/ventilation concept (e.g., lower concentrations at higher ventilation rate), and design. Previous studies report 1,394-2,750 mg CO_2/kg, 5.5-49 mg methane/kg (10,066 mg methane/kg in unfavorable conditions), and 6-118 mg N_2O/kg (per dry larvae biomass harvested). For manure, ammonia emissions are in the order of 7.2 g NH_3/kg dry feedstock. This results in a Global Warming Potential of 2.5-35 g CO_2eq per kg dry larvae biomass harvested (Ermolaev et al., 2019; Mertenat et al., 2019; Pang et al., 2020; Parodi et al., 2020, 2021). However, buildings can also be a lot simpler and cheaper. They can be completely open or simply consist of a concrete slab with a roof and sturdy mosquito netting for pest control. This is more common in small- and medium-scale facilities in (sub)tropical climates.

FIGURE 3: PRODUCTION FACILITY OF PROTIX IN THE NETHERLANDS (LEFT); PRODUCTION TUNNELS BY INSECT ENGINEERS (CENTER); FACILITY OF BIOBUU IN TANZANIA (RIGHT).

Feedstock preparation

Feedstock describes the food used to grow BSF larvae. It can include human and animal manure, wastewater sludge, agri-food byproducts, food waste, slaughterhouse byproducts, and biogas digestate (see section "Feedstocks used" for more detail). Typically, BSF facilities rely on a number of different feedstocks. Because feedstocks are variable, feedstock preparation includes all processes of working towards a homogenous feedstock for rearing of BSF larvae (Gold, et al., 2020). Because biowaste is heavy, it starts with an efficient method of feedstock reception using forklifts, walking floor trailers, bunkers with screw conveyors, or pumps. To balance feedstock production and usage in the BSF facility, some feedstocks may also be stored. However, storage is typically limited to one or two days, although the shelf life can be extended by fermentation. Dry feedstocks can be stored for several weeks or months

Biowaste with variable moisture, nutrient content, or particle size—including other solid waste fractions (e.g., plastic, paper, glass)—can be directly fed to BSF larvae. However, depending on the feedstock, this can lead to high larval mortality or an inefficient bioconversion performance. If solid waste and large inhomogeneities are present, it is more common to (partially) remove solid waste and homogenize/reduce the feedstock's particle size with maceration to a thick, slurry-like consistency. The feedstock nutrient and moisture content of different individual biowastes can be balanced by mixing different feedstocks (Gold, et al., 2020).

The selection of feedstock preparation equipment is highly feedstock dependent but can include depackaging, removal of sand or rocks, maceration (e.g., to 2-5 mm size), fermentation, defatting, mixing, and storage. Other physical, chemical, and microbial pretreatment to break up less digestible fibers are also being investigated (e.g., ultrasound, ammonia) (Peguero et al., 2021). Following preparation, the feedstock can be used for rearing.

Dosing/loading and rearing

Rearing is the process of growing larvae from several milligram weight to harvest weight, which is in the order of 150-250 mg depending on the operation (e.g., feedstock, rearing duration, environmental parameters) and product application (Gold et al., 2018). A defined amount of feedstock (typically in the order of 100-150 mg feedstock/larva per rearing day, according to Dortmans et al. (2021) and Diener et al. (2009)) is manually, semi-manually, or automatically loaded onto beds (e.g., 1.5 x 30 m) or dosed into crates (most commonly 60 x 40 cm or larger) by a crate handling system that includes loading, tipping, and washing of crates; see Figure 4.

FIGURE 4: LEFT: A BED USED FOR BSF LARVAE REARING. RIGHT: SETTING UP THE MACHINE FOR AUTOMATIC LOADING OF A BED WITH FEEDSTOCK (INSECTENGINEERS).

After the feedstock is ready, a defined amount of typically 5-7-day-old larvae (DOL) with a weight of 1-10 mg from the nursery is added on top. Following this, crates are moved manually, semi-manually (e.g., with a forklift), or automatically (e.g., with an automatic guide vehicle—AGV) to the place of rearing and stacked onto each other or placed in racks (Figure 5). Rearing times are in the order of five days to two weeks (Gold et al., 2018). Some facilities feed the units with neonates directly. This makes the separate rearing of 5DOL unnecessary but can lead to fluctuations in the dosage of the number of larvae per unit unless precise counting equipment is used.

FIGURE 5: DIFFERENT DIMENSIONS AND SHAPES OF REARING CRATES AND STACKING METHODS. TOP LEFT: AERATION FRAMES BETWEEN LAYERS OF CONVERSION CRATES (EAWAG). TOP RIGHT: CRATES DIRECTLY STACKED OVER EACH OTHER (BETTER INSECT SOLUTIONS). BOTTOM LEFT: CONVERSION CRATES ARE STACKED CROSSWISE IN THE FACILITY OF INSECTIPRO, KENYA (DIENER/ECLOSE). BOTTOM RIGHT: RAILS USED FOR AUTOMATIC LOADING OF CRATES AT THE PROTIX FACILITY, NETHERLANDS (PROTIX).

Breeding and nursery

Reliable provision of waste treatment and making of product requires a consistent supply of young larval offspring (typically 5DOL). These offspring are supplied by the breeding and nursery unit. In the breeding unit, larval offspring are typically fed with homogenous and nutritious feedstock (e.g., chicken feed, mixture including okara, wheat, maize, rice bran, palm kernel meal, brewers' spent grain) to the prepupal stage. A homogenous and nutritious feedstock in this phase is typical because of its reliability in performance metrics and high egg production. However, this is not a requirement. Following, prepupae are left to pupate in the residue or separated from the residue and pupate with or without pupation material (e.g., a compost-frass mixture, coarse sawdust). Today, pupation is typically achieved in one of the following ways:

- In separate climate room before placement in a fly cage (e.g., as done by Better Insect Solutions).
- In a separate dark cage (e.g., as described in Dortmans et al. (2021)).

- Directly in the fly cage (e.g., in the dark section of the cage by Evo Conversion Systems or InsectoCycle).

As shown in Figure 6, fly cages come in different dimensions and shapes and can be purchased or manufactured from locally available materials.

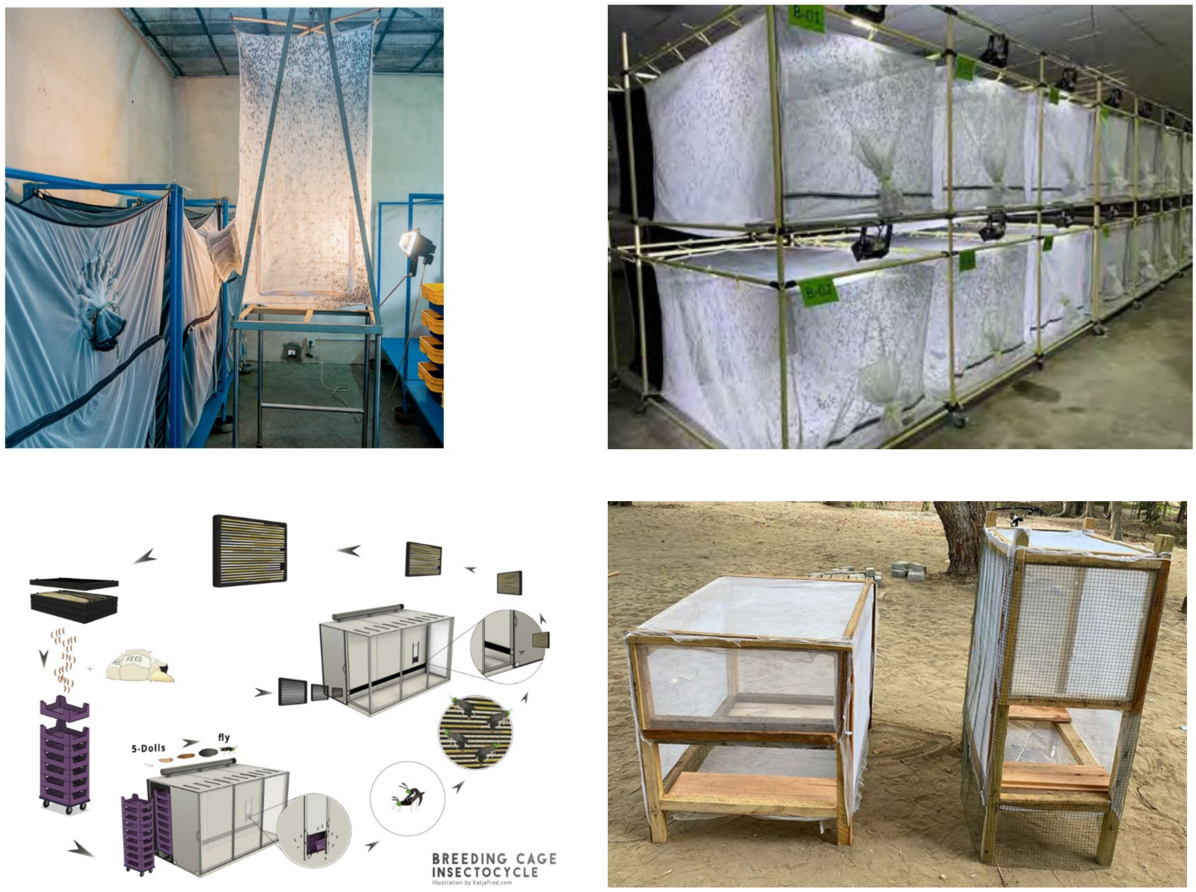
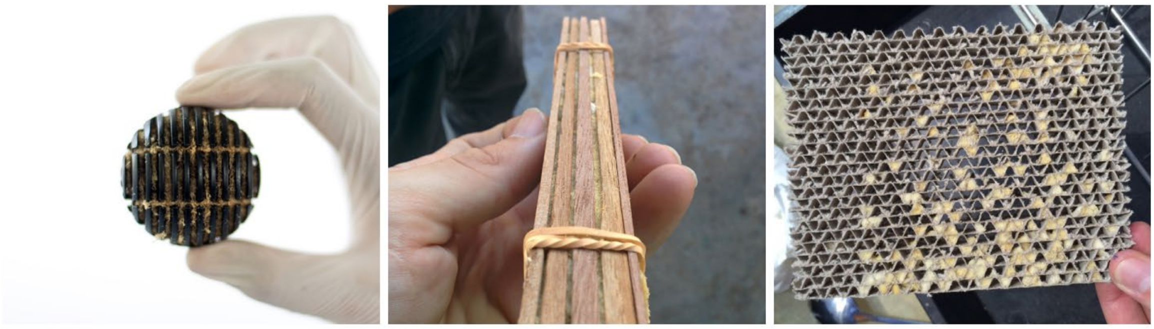


FIGURE 6: DIFFERENT TYPES OF FLY NETS. TOP LEFT: A FLY CAGE IS BEING FILLED WITH FRESHLY HATCHED BSF FROM A DARK CAGE (EAWAG). TOP RIGHT: EVO CONVERSION SYSTEMS SELLS CAGES THAT COMBINE THE DARK (AT THE BACK) AND LOVE CAGE (AT THE FRONT). BOTTOM LEFT: THE INSECTOCYCLE CAGE COMBINES PRODUCTION OF PREPUPAE, PUPATION, AND THE FLY CAGE IN ONE SYSTEM (INSECTOCYLE). BOTTOM RIGHT: A SIMPLE BSF FLY CAGE USING NATURAL LIGHT BUILT FROM LOCALLY AVAILABLE MATERIALS (MOSES MOSHE VELAPHI).

In the fly cage, under natural light or specific artificial light spectra (Heussler et al., 2019; Schneider, 2020; Zhang et al., 2010), BSF mate and female BSF lay eggs on dedicated objects (also called eggies) that can easily be collected by operators (Figure 7). BSF find these eggies because they are placed next to an attractant that lures BSF females to lay eggs nearby. This liquid attractant is typically made of a mixture of different odourous/decaying materials like fermenting fruit, dead flies, or frass.

FIGURE 7: DIFFERENT OBJECTS, SO-CALLED EGGIES, USED FOR COLLECTION OF BSF EGGS.



Harvested eggs are typically placed in a separate climatized room or incubator. Within two to four days, newly hatched larvae (also called neonates) emerge. Frequently, eggs are placed above a homogenous, highly nutritious feedstock. In this way, young larvae directly fall into a moist feedstock and larvae are counted manually based on weight or automatically after typically five days. Following enumeration, larvae are dosed based on weight/number into rearing crates/beds or used again in the breeding unit to produce new flies. Alternatively, eggs hatch above an empty container/funnel and are counted at this stage. At an efficient BSF facility, only in the order of 1.5-3% of young larvae are used for maintaining the nursery (recuperation rate) and 97-98.5% are used for rearing (Dortmans et al., 2021). This recuperation rate is one of the most relevant indicators of a BSF nursery and determines the efficiency of the operation. In order to assess the recuperation rate, measures have to be in place which allow the enumeration and determination of survival and mortality rates of the different stages along the nursery cycle (larval survival, eclosion rate, eggs/fly, hatching rate).

Harvesting

Harvesting larvae and separating them from frass can be done manually, semi-manually, and fully automatedly. Frass is the name given to the feces of insects. Ideally, therefore, the material separated from the larvae consists exclusively of frass. If bioconversion is incomplete, it is mixed with untreated feedstock. In a manual system, crates are removed from the place of rearing and tipped on a sieve that is manually moved. Larvae remain on the top of the sieve whereas the frass falls to the bottom. Alternatively, crates can be tipped automatically by a crate handling system and the larval-frass mixture is transported by a conveyor to a vibrating sieve and wind sifter (Figure 8). Many configurations exist between the strictly manual and fully automated systems.

FIGURE 8: LEFT: MANUAL SEPARATION OF LARVAE AND FRASS (DIENER/ECLOSE). RIGHT: VIBRATING SIEVE TO SEPARATE LARVAE AND FRASS WITH BAGGING (EAWAG).

For both manual and automatic systems, for an efficient separation, it is crucial that the frass has a granular form and does not stick to the larvae. In addition, the larvae need to be larger than the frass, otherwise they end up in the same fraction. When the frass is not granular and larger frass particles remain (or larvae are small), larvae can be harvested by using their tendency to move through a sieve or away from light. However, this is a lot more laborious and will still result in a partial harvest loss because not all products can be separated. In this case, it may be favorable to improve the feedstock preparation (i.e., reduce particle size of initial feedstock) and rearing operation (e.g., higher ventilation rates to remove more water from frass).

Processing

Following harvesting, live wet larvae and frass may be used as harvested, for example as live feed for poultry or fish and a soil conditioner (Ipema et al., 2020; Star et al., 2020; Sindermann et al., 2021). However, the shelf life and product quality/value may be increased by further processing. Frass processes may include composting, drying, milling, pasteurization, and/or pelletizing. Larvae processes may include washing, pasteurization, defatting, blanching, and grinding (IPIFF 2022). Drying increases the shelf life and makes larvae easier to transport. Defatting removes some of the fat and thereby increases the protein content. Protein meal and fat are remaining. Two different concepts exist for processing (Figure 9). Dry processing separates the fat by cold pressing dry larvae (similar to seeds for production of high-quality fats as food). Wet processing separates the fat by decanting ground wet larvae (similar to wet rendering for processing of animal byproducts). Dried larvae, protein meal, and frass can be bagged for transport and fats transported in plastic tanks. Also see sections "Established products" and "Alternative and emerging products" for more details.

Figure 9: Top left: Small-scale press for defatting of dried BSF larvae, producing protein meal (Eawag). Top right: Filling of dryer with wet larvae (Eawag). Bottom left: Large-scale defatting press for removing fat from BSF larvae (Reinartz). Bottom right: Pelletizing and pasteurization of frass (Buehler Group).

Auxiliary processes

Auxiliary processes include all those required to provide inputs for the BSF facility units. In small facilities, this may just include standard water and electricity connection and offices, changing rooms, and wash and break rooms for staff. In larger scale facilities, this may include gas, steam, heat, compressed air to operate pneumatic valves and cylinder, hot water (from electricity, solar, or fossil fuels) to supply hot water for feedstock preparation, HVAC systems and cleaning (e.g., crates, general cleaning), and a SCADA (supervisory control and data acquisition) to control and harmonize all industrial processes.

Feedstocks used

Like farming of plants and animals, undoubtedly, the feedstock is one of the most important factors in BSF rearing (Barragán-Fonseca, 2018; Gold et al., 2018; Lalander et al., 2019). In the right environment, the nutrients and microbes in the feedstock ultimately drive growth and reproductive yield. In a BSF facility, typically several feedstocks exist:

1. *Nursery feedstock*: Homogenous, highly nutritious feedstock for rearing neonate to young larval offspring (typically 3-7 DOL depending on facility operation). Larval offspring are used for breeding and rearing. Feedstock is optimized to minimize mortality. Examples include animal feed or a formulated diet including cereal and corn byproducts, dairy byproducts, chicken feed, okara, rice bran, palm kernel meal, brewers' spent grain.
2. *Breeding feedstock*: Homogenous, highly nutritious feedstock for rearing young larvae to prepupae. Feedstock is optimized to produce prepupa that result in flies that lay a large number of eggs. An example is the nursery feedstock.
3. *Rearing feedstock*: Main feedstock for rearing young larvae until harvest. Feedstocks include anything organic with some nutrients digestible by BSF larvae such as human and animal manure, wastewater sludge, agri-food byproducts, food waste, slaughterhouse byproducts, and digestate. However, the legal framework may restrict the use of some of these feedstocks due to safety concerns (e.g., human and animal manure, slaughterhouse byproducts) or the low bioconversion rate makes its use financially unfeasible. These limitations are due to potential contaminants in the feedstocks (e.g., heavy metals, particularly cadmium and lead, pathogens, chemical and pharmaceutical residues, etc.) that may accumulate in the larvae and make the products unsafe (see section "Food safety" for more detail).

In facilities that have a homogenous and nutritious rearing feedstock, it should be evaluated whether all/some ingredients can be included into the nursery and breeding feedstock without large trade-offs (e.g., high mortality in nursery, low egg yield). This can ensure that young BSF larvae used for rearing are already adapted (e.g., digestive physiology, microbial community) to the feedstock from the parents at a young age.

The rearing feedstock Is most Important due to the following reasons:

- The nursery and breeding feedstock are typically only a small percent of the rearing feedstock. Thus, reliable supply is typically less of an issue.
- Feedstock availability and reliability influence the security of the BSF facility investment.
- Feedstock composition defines the boundary conditions of rearing performance, such as conversion rate, which is directly correlated with product yield and revenue.
- Feedstock composition influences the product quality, such as protein and fat content and fatty acid composition (e.g., lauric acid, omega-3 fatty acids).

- Feedstock costs/revenues can be major (in the order of 25-75% of opex).
- Feedstock composition influences technology requirements and choices (e.g., feedstock preparation, HVAC, product harvesting).

BSF larvae have highest growth and reproduction on feedstocks that are high in digestible nutrients such as protein (10-15% dry mass), carbohydrates (e.g., starch and glucose; 20-30% dry mass), fat (10-15% dry mass), and hemicelluloses and are low in less digestible fibers (e.g., cellulose and lignin) and ash (Barragán-Fonseca, 2018; Beniers & Graham, 2019; Lalander et al., 2019; Liu et al., 2018). However, these values should only be seen as rough guidelines. Firstly, BSF larvae are highly plastic in their digestive physiology. For example, they can grow on feedstock completely free of digestible carbohydrates (e.g., slaughterhouse waste in Gold et al. (2020)). Secondly, the feedstock choice is a trade-off between costs, safety, environmental benefits, and availability/reliability, thus adherence to the optimal feedstock composition for BSF larvae development is not necessarily a mandatory requirement (Gold et al., 2021). For example, one might have access to a highly nutritious feedstock with no safety concerns and a high process performance and BSF-based production quality. However, this feedstock has a high cost and competition exists with other resource recovery options (e.g., biogas, direct use as feed). In contrast, heterogenous food wastes might have a lower rearing performance, produce a more variable product, non-traceable and could contain heavy metals. In line with the summary of the business models, the following examples illustrate that different and suboptimal feedstocks can have similar levels of profitability despite different quality feedstock. These simple examples are hypothetical but based on BSF sector examples (e.g., Protix, Innovafeed, Sanergy, PreZero, Bardee, Hermetia Bio Science). The authors did not have access to open-access financial data of BSF companies using various feedstocks.

- Company A rears BSF larvae on homogenous byproducts from the food industry (e.g., okara, brewers' spent grain, wheat bran, fruit pulp) as they are very nutritious. In addition, they are clean and traceable. The BSF company recovers the feedstock cost through high conversion rates and the production of premium BSF-based products.
- Company B rears BSF larvae on a variety of different urban waste streams such as agri-food byproducts (e.g., fruit and vegetable waste), manure (e.g., cow and pig manure) as well as some packaged food from a supermarket. The company only has to pay for waste collection. Due to the feedstock variability, the rearing performance is lower and more variable than on homogenous food industry byproducts. Consequently, the BSF-based products are of slightly lesser quality. The BSF company receives carbon credits for preventing wastes from entering the landfill. These carbon credits contribute directly to the financial viability of the company (e.g., see Business News Australia (2022) on carbon credits claimed by Bardee) or are important for investors (e.g., mining company Anglo American invested in Sanergy to access carbon credits; see press release by Anglo American (2022) on investment in Sanergy).
- Company C rears BSF larvae on only two feedstocks co-located with a large agricultural company. The feedstock results in low bioconversion rates but the feedstock is free and has no transport costs. Land is provided to the BSF company at

low cost and the BSF-based products are used locally without expensive post-harvest processing.
- Company D (based on project concept by the authors) rears BSF larvae on wastewater sludge with some food waste. The sludge producer currently pays for its landfilling. BSF larvae reduce these disposal costs by reducing the amount that requires landfilling. Because wastewater sludge is high in heavy metals which accumulate in frass, it needs to be disposed of. The BSF larvae are defatted and the fat is used for technical applications. The BSF larvae company receives carbon credits for preventing wastes from entering the landfill.

The nature of the feedstock used is, of course, only one of the factors influencing the economic efficiency of a BSF facility. In the end, it is the combined interaction with the availability of the feedstock, the climate conditions, or the local legal framework that determines the economic viability.

Established products and market overview

One reason why BSF larvae rearing has emerged for feed production and waste management is its production of high-value products (e.g., in comparison to conventional waste treatment products such as compost or biogas). The most common products of BSF facilities are listed below with current market price estimates. BSF larvae can be used as a component for animal feeds (e.g., poultry, pigs, fish, wild birds) (Barragán-Fonseca et al., 2017; Veldkamp et al., 2012; Veldkamp & Bosch, 2015; Wang & Shelomi, 2017) or pet food (e.g., cats, dogs, other zoo animals such as fish or singing birds) (Bosch et al., 2014; Freel et al., 2021). Frass is a soil conditioner and can be further refined into a fertilizer (Fuhrmann et al., 2022; Klammsteiner et al., 2020), used as fuel or used for biogas or biochar production. Like the BSF technology itself, the market for BSF products is in its infancy and therefore subject to great uncertainties. Prices for different products are difficult to determine and depend heavily on local conditions and the degree of their refinement.

This section is based on the authors' experience, statements on the producers' websites, reports by Rabobank (2021) and Bryan, Garnier & Co (Bryan, Garnier & Co 2022), and a study conducted by Reinartz (2021). It should be noted that the prices provided by Reinartz (Figure 10 and Table 1) are self-reported by BSF companies and the data on market size presented by Rabobank are forecasts. It may not reflect the actual prices obtained reliably (i.e., over a certain period of time) at scale (i.e., with significant quantities of product). The large range of prices for the same product can be explained by different pricing based on market (e.g., higher prices in pet food than animal feed), country, business model (e.g., higher prices for B2B than B2C), taxes and subsidies, and product quality (i.e., protein meal prices based on protein content). With the current volatility in agricultural raw material prices, future prices are difficult to estimate.

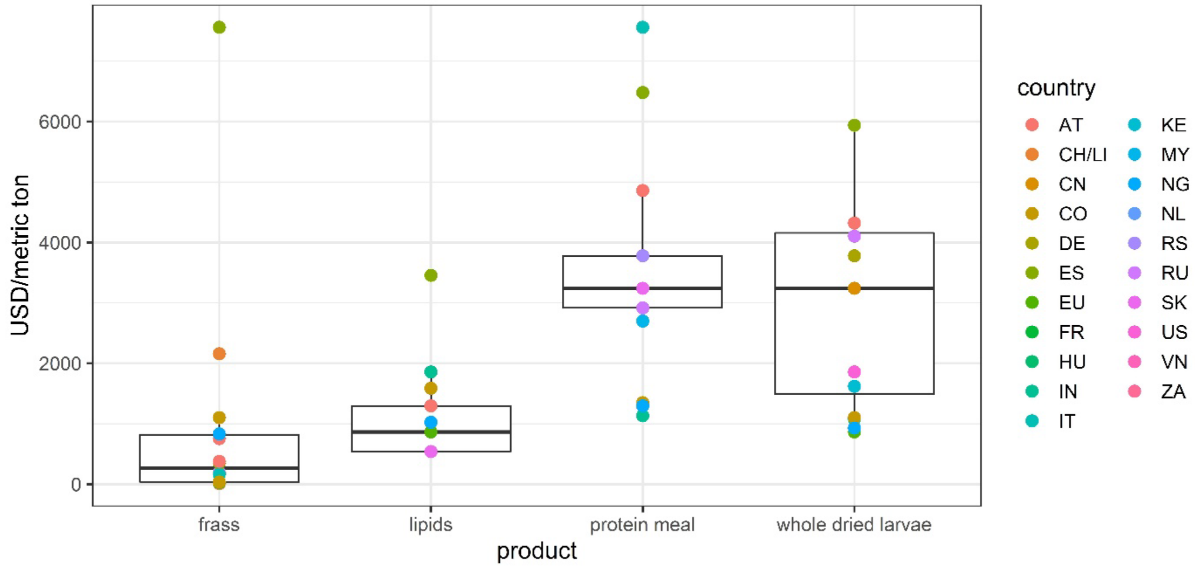


Figure 10: Plot of BSF-based product market prices researched by Reinartz (2021) (self-reported prices by insect companies globally, data collected in 2021, analyzed by Gold Advisory).

Table 1: Summary of BSF-based product market prices researched by Reinartz (2021) (self-reported prices by insect companies globally, data collected in 2021, analyzed by Gold Advisory).

In USD/metric ton	Frass	Fats	Protein meal	Dried larvae
Number of companies	14	13	21	16
Median	270	864	3,240	3,240
Max	7,560	3,456	7,560	5,940
Min	11	540	1,134	864
Standard deviation	1,987	809	1,526	1,554

Similar to the Reinartz report, the reports by Bryan, Garnier & Co and Rabobank make partially questionable assumptions. Bryan, Garnier & Co made general assumptions about the feed market per animal (e.g., 15% for poultry, 30% for aquaculture) without providing support for these estimates. Both reports do not consider regional differences (e.g., North America vs. Europe vs. Asia) and assume no feedstock and legislative limitations. However, it is apparent today that there are large regional differences in demand and supply (e.g., Europe has more producers than the US). In addition, there is already competition around feedstock between BSF larvae rearing and other resource recovery options (e.g., biogas, biofuel, direct feed to pigs and poultry) and there are legal limitations (e.g., in the EU around rearing of BSF larvae on feedstocks that include meat/fish). It is wishful thinking that the EU will allow all feedstocks including food waste, sludge, and manure in the coming years. Also, neither report distinguishes between insect species and products, even though they have a large impact on market size and prices. Given these limitations, the given product pricing and market estimates should thus only be used as broad guidelines.

Rabobank estimates the global market size of the insect market at up to 0.5 million tons/year in 2030 and Bryan, Garnier & Co at 7.3-14.9 million tons/year without providing an estimate on when this potential will be reached. No matter what the true market potential is, considering that a BSF facility produces several hundred to thousands of tons of meal per year and the feed demand is in the order of 4 million (fishmeal) to 200 million tons (soybean meal) and increasing (FAO, 2020; Mottet et al., 2017), the feed demand can be expected to be above the supply of BSF larvae products for many years.

BSF larvae products are typically priced according to current benchmarks and products they aim to substitute or complement. For dried larvae and protein meal, this is fishmeal or other animal meals which have 45-60% protein and are around 1,500-2,500 USD/ton (e.g., 1,600 USD/ton fishmeal on Indexmundi (2022b)). Depending on the larval fat quality (e.g., purity, fatty acid composition), it is used in cooking/vegetable fat, soy fat, coconut fat, or poultry fat in the order of 900-2,500 USD (e.g., 1,200 USD/ton for yellow grease in the US—USDA (2022); 1,580 USD/ton soybean fat—Indexmundi (2022c); 1,300 USD/ton coconut fat—Indexmundi (2022a)). For frass, this is compost or other organic fertilizers. Depending on the market, BSF companies may be able to charge higher prices (e.g., in the order of 25-50%) because they can create additional value for the clients (i.e., feed mills, food producers, livestock farmers; Figure 11). This value may include: 1. (perceived) more sustainable or natural product (e.g., friendly fish label created by Protix), 2. (perceived) better animal welfare, 3. Higher functionality (e.g., protein content in feed, chitin and nutrient in frass).

FIGURE 11: LEFT: FREE RANGE EGGS PRODUCED BY LAYING HENS FED WITH LIVE BSF LARVAE (PROTIX). CENTER: PREMIUM PET FOOD WITH MARKETED BENEFITS FOR PETS AND THE ENVIRONMENT (PROTENGA). RIGHT: TROUT PRODUCED WITH BSF LARVAE IN A PARTICULARLY CIRCULAR WAY (F4F: FOOD FOR THE FUTURE).

Live/fresh larvae: For many animals, insects are part of the natural food supply. This suggests that BSF larvae can be fed live to animals. As an example, in Indonesia, the fresh larval price is in the order of 350 USD/ton (as of 2020). 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. The case that BSF are live and moving is exciting for animals but can make accurate dosing of feed amounts more difficult. In Europe, where BSF are categorized as a farmed animal, feeding of live BSF is a legal grey zone and handled differently between member states.

Frozen fresh larvae/larval pulp: To make live larvae storable, they can be frozen, whole or after mincing—e.g., with a shock freezer and stored in cold storage. This may be desired in the pet food industry where whole fresh larvae or minced larvae are formulated into wet pet food.

Dried larvae: Animal feeds are typically a formulation of several dried feed ingredients. Thus, live/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). As shown in Figure 10 and Table 1, self-reported dried larval prices are around 3,240 USD/ton. Whereas this price may be achieved by selling small amounts in B2C markets, considering the price of fishmeal (1,500-2,500 USD/ton), the authors consider a price of 800-1,500 USD/ton to be more realistic at industrial scale (e.g., selling several hundred tons per year).

Figure 12: Different types of BSF facility products. Top left: Live BSF larvae (Sirajuddin Kurniawan). Top right: Frozen minced larvae by Protix. Bottom left: Protein meal by Protix. Bottom right: Filtered BSF larvae fat from Enviroflight.

Protein meal: Larvae can be defatted with wet or dry rendering (Figure 8). The fat is removed to lower the fat content and thereby increase the protein content. Only this defatting process levels the resulting BSF larvae meal composition with feed benchmarks such as soybean meal and fishmeal (i.e., protein content > 50%, < 15% fat) and facilitates its inclusion in animal feeds. The Reinartz market study concludes a median price of 3,240 USD/ton (Figure 10 and Table 1) which is in line with the wider-use period estimate by Rabobank and prices mentioned by C-level staff of BSF companies as part of the Bryan, Garnier & Co report. Rabobank expects this price to decrease over the next years towards the fishmeal price (plus sustainability, animal welfare, properties) as the supply of BSF larvae meal increases and premium markets (e.g., pets, wild birds, particular food products tailored to environmental conscious citizens) are being saturated. Feed prices are the largest expense for conventional aquaculture and livestock farmers. Consequently, they are more price sensitive unless they can pass it on to the ultimate consumer of the animal food product.

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 (Borelli 2021; Leong 2015). The median larval price in the Reinartz report is 864 USD/year (Figure 10 and Table 1). This is in the order of the soy fat and poultry fat price before the Russian invasion of Ukraine, which has increased feed and fat prices by several hundred USD/ton. If fat is high in omega-3 fatty acids (absorbed from the feedstock) or used in high-value markets (e.g., replacement for coconut fat), much higher prices in the order of 1,000-2,500 USD/ton can likely be achieved. The fat content of the larvae and the composition of the fatty acids depend strongly on the food source (Rodrigues et al., 2022). This plasticity can be exploited to produce a higher or lower fat content in the larvae, depending on the intended use.

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 due to its frequently lower value than the above-mentioned larval-based products. The frass price can be as low as below 50-100 USD/ton or as high as several hundred USD/ton (see 270 USD/ton, Reinartz (2021) (Figure 10 and Table 1). However, over the years, 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.

Alternative and emerging products

Chitin/Chitosan

The exoskeleton of insects contains the polymer chitin (larvae: 8-12% dry mass; exuviae: 22-26% dry mass) (Araujo et al., 2022; Triunfo et al., 2022). However, chitin in feed can have negative effects on the growth of livestock such as fish, poultry, and pigs. High amounts (e.g., 10%) are often undesired as chitin is not digested by those animals. For this reason, feed mills demand products with a low chitin content. Chitin may still be added as a separate component in the desired quantity, if required. For insect producers, it is therefore desirable to find a separate market for the extracted chitin. Due to their properties and applications (e.g., bioplastic, pharmaceuticals, agriculture), the growing demand for chitin and chitosan has stimulated the market to find additional alternatives to the current commercial source (crustaceans). Biodegradability, biocompatibility, non-toxicity, hemostaticity, bioadhesiveness, and immunostimulant activity are some useful properties of chitin and chitosan that make them polymers of economic interest. Chitin and chitosan find application in the food industry, agriculture, wastewater treatment, tissue engineering, biomedical, biotechnological, sanitary, and cosmetics sectors, and in the textile and paper industries. Prices for chitin vary depending on its purity and application. According to Global Industry

Analysts, Inc., the global market for chitin and chitosan derivatives, estimated at 106,000 tons in 2020, is projected to reach a size of 281,000 tons by 2027, growing at a compound annual growth rate (CAGR) of 14.8% over the analysis period of 2020 to 2027. According to a BCC Research report published in 2017, the global chitin and chitosan derivatives market should reach USD 4.2 billion by 2021 from USD 2.0 billion in 2016 at a CAGR of 15.4%, from 2016 to 2021 (Perez & Wertz, 2022). A facility treating 10 tons of organic waste per day produces potentially about 36-60 kg of chitin from larvae and 1-1.5 kg from pupal exuviae.

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 is able to adsorb heavy metals and neutralize lipid peroxidation products (Ushakova et al., 2018). 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. VWR, one of the major suppliers of laboratory chemicals, sells melanin at a price of USD 440/g (VWR, 2022). In black soldier flies, the content of melanin varies among the life stages from 5.7 mg/g dry mass in larvae to 34 mg/g dry mass in pupae (Ushakova et al., 2018). Each BSF pupa thus contains melanin worth 3 USD.

Biochar

Biochar can be produced from pyrolysis of organic material. Pyrolysis is the combustion of organic material in the absence of oxygen. Biochar can be used as soil conditioner. Because the carbon in biochar is very stable in the soil, it is also emerging as a solution for capturing the carbon taken up during the production of the organic material and storing it in the soil. Thereby, it is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of contributing to reducing global climate change. Alternatively, 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. Lalander et al. (2018) found a biogas production from food waste BSF frass of 576 m^3/ton organic matter with a methane percentage of 61% as compared to 695 m^3/ton organic matter and 64% for the original food waste. BSF larvae rearing thus decreased the biomethane potential of food waste by around 20%. In comparison to common biogas feedstock, BSF frass (454 m^3/t DM) produces comparable amounts of biogas per ton as pig slurry (325 m^3/t dry mass), slaughter byproducts (575 m^3/t dry mass), and sewage sludge (300 m^3/t dry mass), based on dry matter (Elissen et al., 2019). A facility treating 10 tons of waste has the potential to produce 100-120 m^3 of biogas. Frass biogas production is likely highly dependent on feedstock (e.g., initial biogas potential of feedstock before BSF larvae rearing) and BSF rearing operation (e.g., how much biogas-producing material is taken up into larvae or consumed by microbes).

Genetic quality and improvements

Worldwide, BSF with a very different genetic makeup exists (Kaya et al., 2021). As the BSF reproduce, their genetic makeup is continuously reshuffled and as the BSF has a short life cycle (6-8 weeks), this happens quite often, so the genetic makeup is always in movement. In addition, a BSF with the same genetic makeup is very good at expressing different phenotypes/fitness depending on the environment and feedstock. A decrease of the genetic quality resulting from a decrease in fitness is a major concern for BSF companies. Rearing of animals (including insects) in captivity can lead to the loss of genetic diversity by inbreeding (Huis & Tomberlin, 2016). This can result in loss of insect fitness and development of unfavorable properties. However, inbreeding is lower at very high population sizes, as in industrial BSF colonies. One way to identify inbreeding is to monitor key performance indicators of the colony (e.g., eggs per fly/m^3 cage, neonates per prepupae, etc.) daily and plot them over time. One way to decrease inbreeding is to use a sufficient starting population of at least 1,000 individuals and to avoid bottlenecks (e.g., decimation of the population by accidents to a few hundred individuals). To introduce new genes, BSF from another BSF colony could be added. Despite being competitors, it is therefore advisable for BSF companies to network with other companies in order to exchange on biology and operational issues as well as having access to a biological backup. BSF genetics and selection is a fairly new research area but has gotten more attention in the past year (Sandrock et al., 2022). Industry experts expect developments to follow those of plants and livestock (e.g., poultry), which have seen enormous improvements through genetic improvements and artificial selection. For example, in broiler chicken, improvements of 43% in feed conversion ratio and 243% in body weight were achieved in 45 years of artificial selection and the environmental impact caused by greenhouse gas emissions from broiler production decreased by 1.6% per year from 2014 to 2018. Recently, a study has shown +39% in larval weight, +34% in wet crate yield, and +26% in dry matter crate yield through 16-generation artificial selection programs (Facchini et al., 2022). One study so far has used CRISPR/Cas9-based gene editing to yield BSF with unique abilities (flightless and enhanced feeding capacity phenotypes) (Joly & Nikiema, 2019). Several partnerships exist between BSF producers and genetic companies (e.g., Nasekomo and Groupe Grimaud, Protix and Hendrix Genetics).

Influence of operational structure on efficiency and personnel

Regardless of the capacity of a BSF operation, efficiency and productivity stand or fall with the existence of clear production processes. The areas of feedstock reception and preparation, nursery and breeding, rearing, product harvesting and processing, and hygiene management must be coordinated. The fact that insects have plastic life cycles due to their biology—i.e., development time and mating behavior are influenced by environmental conditions—means that production processes and all individual tasks must be clearly defined and monitored. This is the only way to ensure constant processing of defined waste quantities and consistent BSF-based product output. That is why standard operating procedures (SOPs) need to be in place for all units. The existence of SOPs also makes it possible to define staff requirements more clearly and to use less qualified staff for individual tasks. In addition to controlling the actual production process, SOPs also cover the areas of maintenance and cleaning (e.g., HACCP: hazard analysis and critical control points). This enables legal requirements for hygiene and working conditions to be met, but ultimately also increases staff job satisfaction.

Regulatory framework

The production and distribution of BSF-based products used for food production via animal feed (e.g., fish, eggs, meat) is regulated in order to protect human and animal health. This can include frass used for food production. Other, currently more niche markets such as BSF-based products for applications in the cosmetics, biofuel, and biobased applications industry (e.g., chitin, bioplastics) have no or fewer restrictions and are therefore not further covered here. The goal of regulation is to prevent contaminants from entering the food system and produce nutritious and safe foods (Lähteenmäki-Uutela et al., 2021). In parallel to development of the BSF sector, the past decade has seen the implementation or drafting of legislation across the world. In many regions, this was initiated or supported by academia, BSF companies, and regional insect associations, including the following:

- 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)
- Feed manufacturing organizations

Depending on the country, these regulations may be defined and enforced by various regulatory bodies including food safety, veterinary, environment, and agriculture. They may include the following:

- Hygiene standards for rearing of insects and production of insect-based products
- The type of insect allowed for rearing as feed
- The feedstock allowed for rearing of BSF larvae as feed
- Processing methods for BSF-based products (e.g., certain heat, time, and pressure) and/or quality standards (e.g., concentration of heavy metals, mycotoxins, and indicator microbial organisms)
- The form of BSF-based products that can be used for pets and livestock
- The type of livestock to which BFSL-based feeds can be fed

In general, the BSF sector has welcomed the establishment of regulations because it can give it a clear direction on how to operate, even though it may also be limiting (e.g., for feedstock, limitation to feed BSF-based products to certain animals, heat treatment of frass in Europe). This is especially relevant for capital-intensive, industrial-scale projects. Getting all permits in place may take from several weeks to 9-18 months or more. Next to these BSF-specific regulations, other licenses may be required, including general business license, license to manufacturer feed, environmental impact assessment, HACCP, license for emissions (e.g., water, wastewater, CO_2, NH_4, particulate matter), and license to transport and treat waste.

Despite the development of BSF-specific regulations, in many places, the legislation for BSF production is yet lacking, unclear, or disabling. Reasons for this vary between countries and include a generally low food safety legislation, history of food safety scandals, or the high demand for animal feeds in order to provide enough food. One needs to consider that for over a hundred years, the goal of food safety authorities has been to separate insects as much as possible from food products because they are associated with poor hygiene and can distribute human and animal diseases. Due to the new nature of the process and products, complete and reliable data for policymakers is still lacking. Moreover, several dramatic food safety scandals have been associated with typical BSF larvae rearing feedstock (e.g., food waste with products from animal origin) such as the foot and mouth disease, mad cow disease (bovine spongiform encephalopathy, BSE), transmissible spongiform encephalopathies, and more recently, the African swine fever. Yet, considering legal changes only in the past years (e.g., allowing BSF larvae for poultry feed in Europe) and the issues around waste management and food production, the authors expect the development of enabling policies to continue.

European Union (EU)

Food safety and thereby most regulations regarding rearing of BSF larvae and use as feed are harmonized across all 27 member states (IPIFF 2022). The EU has some of the most complete but also strict regulations. The regulations are summarized in Figure 13 and information about the 26 relevant EU regulations can be found in the IPIFF Guide on Good Hygiene Practices (IPIFF 2022). Regarding feedstocks, BSF larvae are considered farmed animals. Consequently, they can only be reared on certified livestock feed materials and traceable agri-food and pre-consumer byproducts (including eggs and milk, strictly no fish or meat). Food waste (e.g., household, restaurants, canteens), manures, wastewater sludge, and slaughterhouses are not allowed. Regarding animals for which BSF-based products can be used, BSF larvae oils can be used to feed all animals, including ruminants. The feeding of live larvae to non-ruminants is not harmonized across the EU and is up to local bodies which may allow (e.g., the Netherlands) or prevent it. Protein meal falls under the legislation of processed animal proteins (PAPs). The TSE (transmissible spongiform encephalopathies) legislation (regulation (EC) No 999/2001) prohibits the use of any PAP when intended as feed for ruminants and non-ruminant farmed animals (excluding fur animals). However, particular legislation has allowed use of insect protein meal (insect PAP) in aquaculture (since 2017, Regulation (EU) 2017/893 amending Annex IV section F of Regulation (EC) No 999/2001) and for pigs and poultry (since 2021, Regulation 2021/1372 amending Annex IV of Regulation (EC) No 999/2001). Consequently, protein meal is allowed as feed for pets, pigs and poultry at the time of writing this report. The EU also has a specific regulation regarding the frass. It can only be placed on the EU market following heat treatment at 70°C for one hour.

US and Canada

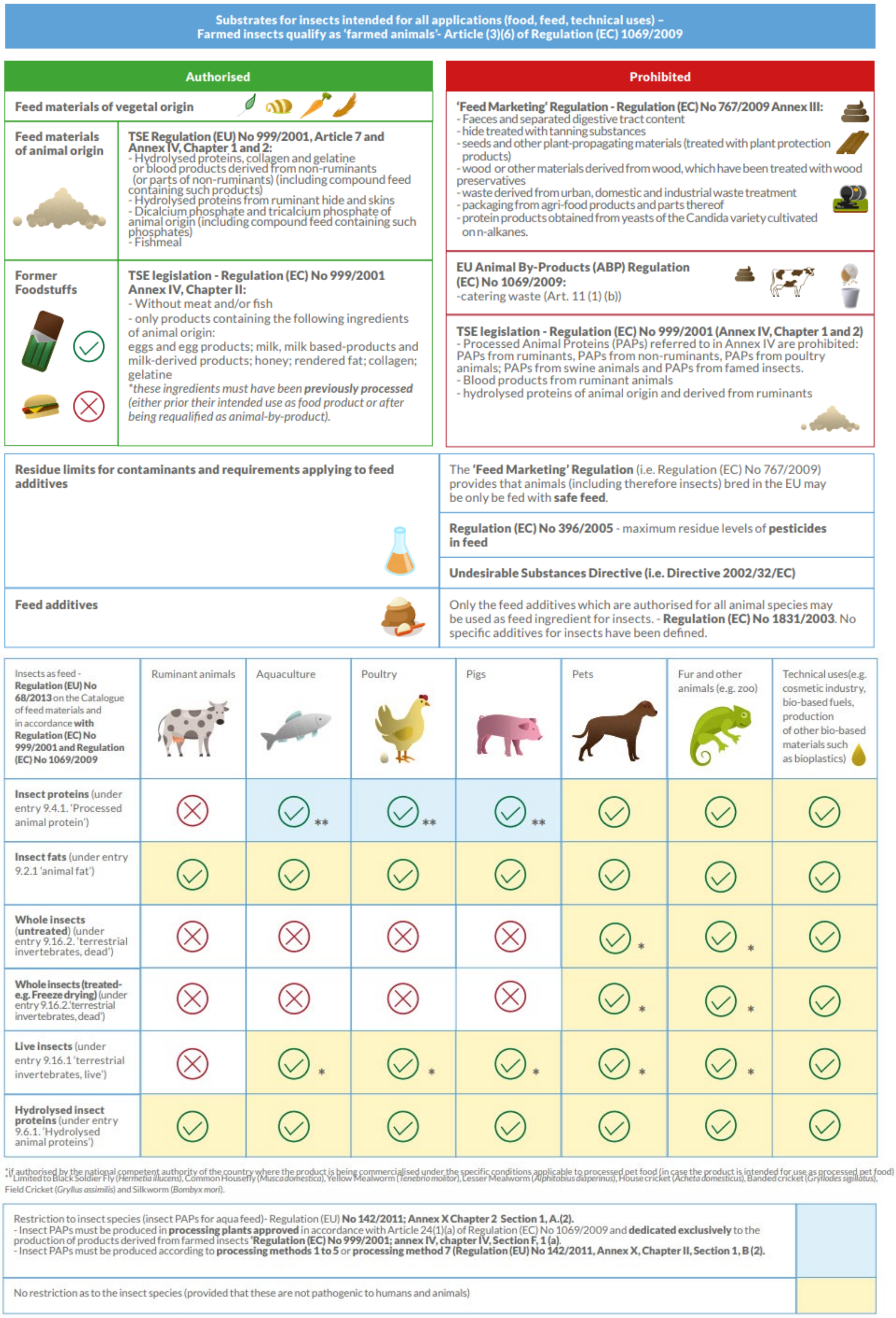
The Food and Drug Administration (FDA) and Association of American Feed Control Officials (AAFCO) are the most relevant bodies regarding BSF larvae as feed. In the US, feed regulations are enforced by state and federal regulatory officials who provide subject matter expertise in animal science, animal nutrition, feed label compliance, field operations for inspection staff, and program administration. AAFCO membership includes not only US state and federal regulatory officials but has grown to include international membership of Canada and Costa Rica. AAFCO has allowed use of dried whole BSF larvae and protein meal in aquaculture for salmonids such as salmon, trout, and char (Lähteenmäki-Uutela et al., 2021). BSF larvae can only be reared on approved feed-grade materials (i.e., Generally Recognized as Safe (GRAS) approved), including pre-consumer food waste as well as other food manufacturing byproducts such as brewers' spent grain. Several states also allow insect-based pet foods, while other states wait for AAFCO and FDA decisions. Pet treats do not have to comply with all AAFCO regulations, as they are not a source of complete nutrition (Lähteenmäki-Uutela et al., 2021). Interests of the insects industry in North America are represented by the North American Coalition for Insect Agriculture (NACIA).

Australia

Australia and New Zealand do not have standalone legislation or specific government regulations on insect farming, but the Insect Protein Association of Australia (IPAA) has developed guidelines for its members (Lähteenmäki-Uutela et al., 2021). Non-members of IPAA are not bound by the rules, and they are yet to be made available for public access. BSF larvae may be used as feed for aquaculture in all states, and as feed for poultry in NSW, ACT, Tasmania, Victoria, and Western Australia. Insects used for feed are not to be fed with meat, manure, and catering waste. Live and untreated (heat) BSF larvae for feed are not permitted in Australia. In contrast, pet food in Australia is self-regulated with voluntary industry standards of the Pet Food Industry Association of Australia (PFIAA). In Australia, the Insect Protein Association of Australia (IPAA) advocates for the Australian insect industry to be a global leader in the food and feed landscape.

Asia

Little information is available on the regulation of BSF larvae rearing and BSF-based products in Asia (Yen, 2015). To the authors' knowledge based on correspondence with industry experts, regulatory hurdles are low, meaning that BSF larvae can often be reared on non-traceable pre- and post-consumer food wastes as well as wastewater sludge. In China, BSF larvae is a promising solution for waste management for the enormous amounts of food waste. At the same time, China has an enormous demand for animal feed. In China, new feed raw materials need to be authorized, and authorized feed materials are added to the Feed Materials Catalogue. In Japan, the Ministry of Agriculture, Forestry, and Fisheries has given the Act on Safety Assurance and Quality Improvement of Feeds, which includes the maximum limits for pesticide residues, heavy metals, mycotoxins, and melamine. Feed manufacturers such as BSF companies, importers, and/or dealers must submit notification prior to starting a business. In Singapore, the Singapore Food Agency (SFA) is responsible for regulating animal and bird feed. As part of the licensing requirements for establishment of BSF to animal feed facilities, the SFA requires that the feedstocks used to feed the insects are properly handled and traceable to ensure the safety of insect-derived animal feed. This is very different to many other countries across Asia (e.g., China) and highlights that regulations may vary greatly among countries. The Asian Food and Feed Insect Association represents the interest of its members from the industry and academia working with insects as food and feed in Asia.



Substrates for insects intended for all applications (food, feed, technical uses) –
Farmed insects qualify as 'farmed animals'- Article (3)(6) of Regulation (EC) 1069/2009

Authorised		Prohibited
Feed materials of vegetal origin		**'Feed Marketing' Regulation - Regulation (EC) No 767/2009 Annex III:** - Faeces and separated digestive tract content - hide treated with tanning substances - seeds and other plant-propagating materials (treated with plant protection products) - wood or other materials derived from wood, which have been treated with wood preservatives - waste derived from urban, domestic and industrial waste treatment - packaging from agri-food products and parts thereof - protein products obtained from yeasts of the Candida variety cultivated on n-alkanes.
Feed materials of animal origin	**TSE Regulation (EU) No 999/2001, Article 7 and Annex IV, Chapter 1 and 2:** - Hydrolysed proteins, collagen and gelatine or blood products derived from non-ruminants (or parts of non-ruminants) (including compound feed containing such products) - Hydrolysed proteins from ruminant hide and skins - Dicalcium phosphate and tricalcium phosphate of animal origin (including compound feed containing such phosphates) - Fishmeal	**EU Animal By-Products (ABP) Regulation (EC) No 1069/2009:** -catering waste (Art. 11 (1) (b))
Former Foodstuffs	**TSE legislation - Regulation (EC) No 999/2001 Annex IV, Chapter II:** - Without meat and/or fish - only products containing the following ingredients of animal origin: eggs and egg products; milk, milk based-products and milk-derived products; honey; rendered fat; collagen; gelatine **these ingredients must have been **previously processed** (either prior their intended use as food product or after being requalified as animal-by-product).*	**TSE legislation - Regulation (EC) No 999/2001 (Annex IV, Chapter 1 and 2)** - Processed Animal Proteins (PAPs) referred to in Annex IV are prohibited: PAPs from ruminants, PAPs from non-ruminants, PAPs from poultry animals; PAPs from swine animals and PAPs from famed insects. - Blood products from ruminant animals - hydrolysed proteins of animal origin and derived from ruminants

Residue limits for contaminants and requirements applying to feed additives	The **'Feed Marketing' Regulation** (i.e. Regulation (EC) No 767/2009) provides that animals (including therefore insects) bred in the EU may be only be fed with **safe feed**. **Regulation (EC) No 396/2005** - maximum residue levels of **pesticides in feed** **Undesirable Substances Directive (i.e. Directive 2002/32/EC)**
Feed additives	Only the feed additives which are authorised for all animal species may be used as feed ingredient for insects. - **Regulation (EC) No 1831/2003**. No specific additives for insects have been defined.

Insects as feed - **Regulation (EU) No 68/2013** on the Catalogue of feed materials and in accordance **with Regulation (EC) No 999/2001 and Regulation (EC) No 1069/2009**	Ruminant animals	Aquaculture	Poultry	Pigs	Pets	Fur and other animals (e.g. zoo)	Technical uses(e.g. cosmetic industry, bio-based fuels, production of other bio-based materials such as bioplastics)
Insect proteins (under entry 9.4.1. 'Processed animal protein')	✗	✓ **	✓ **	✓ **	✓	✓	✓
Insect fats (under entry 9.2.1 'animal fat')	✓	✓	✓	✓	✓	✓	✓
Whole insects (untreated) (under entry 9.16.2. 'terrestrial invertebrates, dead')	✗	✗	✗	✗	✓ *	✓ *	✓
Whole insects (treated- e.g. Freeze drying) (under entry 9.16.2 'terrestrial invertebrates, dead')	✗	✗	✗	✗	✓ *	✓ *	✓
Live insects (under entry 9.16.1 'terrestrial invertebrates, live')	✗	✓ *	✓ *	✓ *	✓ *	✓ *	✓
Hydrolysed insect proteins (under entry 9.6.1. 'Hydrolysed animal proteins')	✓	✓	✓	✓	✓	✓	✓

*if authorised by the national competent authority of the country where the product is being commercialised under the specific conditions applicable to processed pet food (in case the product is intended for use as processed pet food)
**Limited to Black Soldier Fly (*Hermetia illucens*), Common Housefly (*Musca domestica*), Yellow Mealworm (*Tenebrio molitor*), Lesser Mealworm (*Alphitobius diaperinus*), House cricket (*Acheta domesticus*), Banded cricket (*Gryllodes sigillatus*), Field Cricket (*Gryllus assimilis*) and Silkworm (*Bombyx mori*).

Restriction to insect species (insect PAPs for aqua feed)- Regulation (EU) **No 142/2011; Annex X Chapter 2 Section 1, A.(2).** - Insect PAPs must be produced in **processing plants approved** in accordance with Article 24(1)(a) of Regulation (EC) No 1069/2009 and **dedicated exclusively** to the production of products derived from farmed insects **'Regulation (EC) No 999/2001; annex IV, chapter IV, Section F, 1 (a).** - Insect PAPs must be produced according to **processing methods 1 to 5** or **processing method 7 (Regulation (EU) No 142/2011, Annex X, Chapter II, Section 1, B (2).**	(blue)
No restriction as to the insect species (provided that these are not pathogenic to humans and animals)	(yellow)

Figure 13: Overview of legislation concerning the feeding (top) and use (bottom) of insects in the European Union (IPIFF 2022).

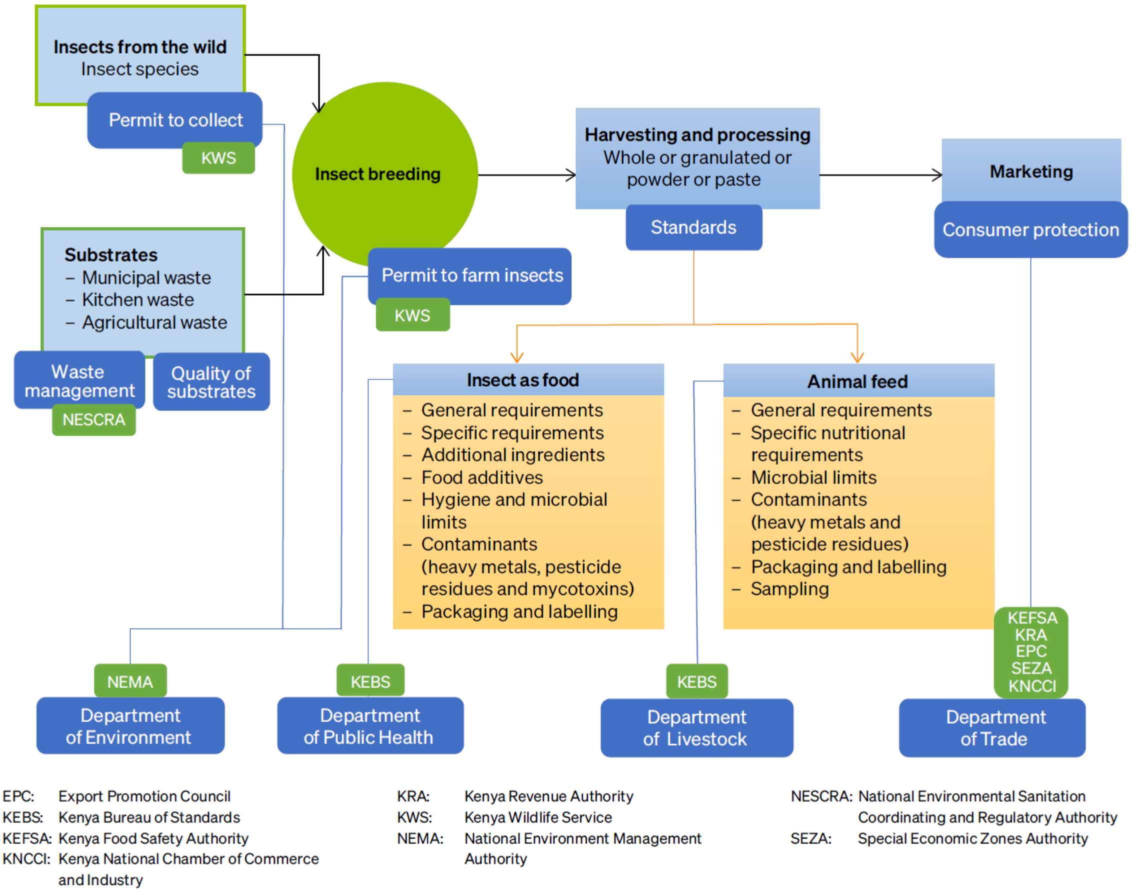


FIGURE 14: REGULATORY PROCEDURE FOR THE INSECT COLLECTION AND PRODUCTION CHAIN AND EMERGENCIES IN RELATION TO SAFETY IN KENYA (ALAGAPPAN ET AL., 2022).

Africa

In many countries in Africa, the development of specific regulations around BSF larvae are currently underway. A study from 2020 reported that specific regulations were absent in most of Sub-Saharan Africa regarding the production and distribution of BSF-based products (Nakimbugwe et al., 2020). However, recently, some regulations have been established, drafted, or are being developed (Alagappan et al., 2022). Examples include Kenya, Uganda, Tanzania, and Malawi. In Uganda and Kenya, the National Bureau of Standards has set several standards regarding BSF, including defining nutritional, microbial, heavy metals, and aflatoxin concentrations in BSF larval products (Uganda: US 2146:2020 and US 1712:2017; Kenya: KS 2922-1:2020). Figure 14 summarizes the legal framework in Kenya and shows how producers' interactions with a number of government bodies is needed. No specific regulations exist in Zimbabwe, Nigeria, South Africa, Cameroon, and Ghana. To the authors' knowledge, typically no limitations on what feedstock BSF larvae are reared as well as to which animals they can be fed exist across Sub-Saharan Africa. However, the lack of specific regulations for BSF does not mean that there are no regulations to follow. Frequently, regulations exist to produce and sell feed and fertilizer. For example, to manufacture, import, or sell feed or pet food in South

Africa, the product must be registered according to the Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act 1947, including a comprehensive analysis of the product by an accredited laboratory. In Nigeria, both local manufacturers and importers of feed must apply for registration for each product with the Veterinary Medicine and Allied Products directorate. At the time of writing this report, there is not a single organization in Africa that represents the interests of the different stakeholders in the insect sector and lobbies for a transnational regulation – but regional or local advocacy groups exist.

Global trading of insect-based products

In general, feed markets are enormous in quantity and highly globalized. Because the number of BSF-based feeds or feed ingredients is relatively small and local markets exist, trading is not yet as global as similar markets like soybean and fishmeal. Frass is often used in the region (e.g., < 100 km) due to lower market value, higher moisture content, and high amounts. To the authors' knowledge, some examples of global trading of insect-based products include:

- Selling of BSF eggs (e.g., from Africa to Europe or across a continent)
- Selling dried BSF larvae from Africa to Europe (e.g., for use as a bird feed with low regulation level. Similarly, this may exist in the Americas and Asia)
- Some companies (e.g., in Asia and Africa) produce BSF larvae according to EU regulation to be able to sell to any market (EU has probably the strictest regulation requiring registration in TRACES: Trade Control and Expert System)

In general, companies exporting BSF-based products can be expected to have to follow the same regulations as the region they are importing to (e.g., EU or North America).

Environmental, social, and health considerations

Environmental sustainability

Improved sustainability is a main driver of the BSF sector, be it as an intrinsic motivation for operators to build up a BSF facility or as an argument of businesses to attract funding and to gain trust from the customers and the public. Sustainability is defined as the ability of a resource or system to be maintained at a certain rate or level and it is the avoidance of the depletion of natural resources in order to maintain an ecological balance. It has an environmental, social, and economic dimension.

Related to environmental sustainability, depending on the business model of the BSF company, typically two motivations exist:

- To produce more sustainable insect-based products than current benchmarks, e.g. pet and animal feeds, such as animal byproducts, soybean meal, or fishmeal.
- To treat waste with a lower environmental impact than treatment alternatives such as (unmanaged) landfilling, composting, incineration/open burning, etcetera.

Today, the expression "sustainable" is typically used to describe the environmental dimensions, thus, whether fewer resources are used for the production of BSF-based products or for waste treatment in comparison to product/treatment benchmarks. To date, no one has systematically determined the economic and social impact of BSF facilities and products. Even the environmental impact is notoriously difficult to measure, and the outcome is highly dependent on the data quality and what boundary conditions and functional units are used. Inaccurate and incomplete data as input for an environmental impact assessment will produce inaccurate assessment of the environmental impact. The results of environmental impact assessment are highly case dependent, but some general conclusions exist (Bosch et al., 2019; Smetana et al., 2021, 2016, 2019):

- BSF larvae products are not necessarily more sustainable than the comparable feed ingredients such as soybean and fishmeal that they aim to replace/complement. Outcomes depend on facility boundary conditions (see below details on feedstock, product, and use of energy and water).
- BSF larvae can be farmed with lower land use than comparable feed ingredients such as soybean and fishmeal.
- Emissions, global warming potential, use of fresh water source, etcetera depend on:
    - Feedstock used: Typically, only feedstocks that are not already directly used as animal feed or for higher value processes (e.g., algae as food, direct food production, etc.) produce BSF-based products with a lower environmental impact than a feed benchmark. Wastes that currently pollute the environment

have the highest potential to produce environmental benefits in comparison to the status quo. Transport distances are relevant to consider.
    - Type of product: Processing of larvae and frass, specifically drying and pasteurization/blanching, requires significant amounts of energy vs. live larvae and frass harvested as is.
    - Type of energy use: Specifically, climatization/ventilation (i.e., HVAC) and processing requires significant amounts of energy. The source also matters, for example, fossil fuels vs. renewable energy such as solar or wind. It is beneficial to co-locate with a process that currently produces waste heat.
    - Type of water: Mostly relevant in semi-arid and arid regions. Here, water use should be optimized and water recycled.
- Environmental benefits are compared to benchmarks (e.g., soybean and fishmeal). The environmental benefit of these is poorly quantified (e.g., biodiversity loss, overfishing, socio-economic impact). The environmental benefits of soybean and fishmeal is regionally different (e.g., fishmeal from fish processing vs. catch).

Social and economic impact

Even though environmental sustainability is typically most emphasized in the sector, BSF larvae rearing offers several socio-economic opportunities with the potential to increase the livelihood, economic sustainability, and social status of individuals. In addition, increased food security and savings in foreign currency can increase the stability of societies and make them more resilient to interruptions of the global food system. This section is based on the authors' experience and Abro et al. (2020).

Create new jobs: BSF facilities can generate new jobs across the entire value chain. This may include staff at regulators, technology providers, insect-producing companies or product processors and distributors, and additional farmers due to lower feed or fertilizer prices. This is especially relevant for many low- and middle-income countries where unemployment, especially for women and the young, is high.

Provide alternative job opportunities: Globally, the agricultural sector is under pressure due to increasing raw material prices and the effects of climate change, for example. BSF larvae rearing offers new business opportunities to members of the agricultural sector (including small holder farmers) and beyond. For farmers and other actors, it can also diversify their income generating opportunities comparable to beekeeping.

Include vulnerable groups such as woman, unskilled laborers, ex-combatants, victims of war/abuse, and the young: BSF facilities can be almost fully automated in large industrial facilities, requiring few skilled laborers. However, they can also be fully manually operated by anyone following thorough training with low requirements for capital, land, and water, including women, unskilled laborers, and the young.

Food security: As highlighted by supply chain interruptions during the COVID-19 pandemic or increasing grain prices due to the 2022 invasion of Ukraine by Russia, the food system is interconnected and global. Thus, it can be advantageous to produce more food locally requiring feed and fertilizer which are products of BSF facilities. Such local food production can ultimately also contribute to societal stability because food supply and prices can contribute to societal instability.

Save foreign currency: Many low- and middle-income countries have many urgent development activities for which they have to spend foreign currency. Countries could save foreign currency spending on feeds and fertilizers by substituting imported products (e.g., feeds and fertilizers) with insect-based products. These savings can be used for other development activities (e.g., transport, health, education).

Disgust towards BSF-based products

Many people feel disgust when imagining eating insects. Because they are fed on decaying organic matter, BSF larvae have rarely been considered as food. Still, possible reservations due to disgust should be reconsidered—for example, for chickens fed with BSF larvae or soap produced with BSF larvae fat. However, we are in an in-between zone in the pet food sector, as it is ultimately people who choose and buy the food for their pets. So aversion to insects in the product can still have a negative impact on acceptance, but not as strong, because the buyer is not the consumer (Higa et al., 2021).

Food safety

BSF larvae feed on decaying organic matter that naturally includes contaminants that should not enter the human food chain via feed and fertilizer (see Table 2).

TABLE 2: POTENTIAL HAZARDS IN BSF LARVAE FEEDSTOCKS. A = MYCOTOXINS, B = HUMAN/VETERINARY DRUGS, C = AGRICULTURAL CHEMICALS, D = MICROBIAL PATHOGENS AND THEIR TOXINS (E.G., BOTULINUM TOXIN), E = METALS, AND F = MISFOLDED PRION PROTEINS (Biancarosa et al., 2017; Food and Agricultural Organization (FAO), 1997; C. Lalander et al., 2013, 2016; Niermans et al., 2021; Purschke et al., 2017).

Waste	Hazard
Human feces and excreta	B, D
Wastewater and fecal sludge	B, D, E
Animal manure	B, C, D
Slaughterhouse waste	D, F
Household waste	D, E
Cereal-based byproducts	A, D
Food & restaurant waste	A, D
Food processing waste	A, D

In general, two groups of contaminants can be distinguished:

- Group 1: Contaminant can be removed by post-harvest processing (e.g., heat treatment, pressure treatment, etc.).
- Group 2: Contaminant accumulates in the larvae and frass and cannot be removed by post-harvest processing.

For contaminants of group 1 (e.g., typical pathogens such as *Salmonella*, *E-coli*), whether or not the BSF-based product can safely be used as feed or fertilizer largely depends on the product processing method. This is why, globally, many food safety authorities describe concentrations of key microbial (e.g., spores, pathogens) and chemical (e.g., heavy metals such as cadmium and lead, mycotoxins such as aflatoxin B1, as well as pharmaceutical and pesticide residues) parameters that need to be analyzed and below certain thresholds. Some food agencies also describe post-harvest processing regimes (e.g., certain pressure, temperature, and time combinations). It has been shown that suitable killing methods (e.g., blanching) and drying at sufficiently high temperatures (60-100°C depending on microbial load) for an extended period of time can bring the contamination in the larvae below common microbial quality standard levels (Bessa et al., 2021; Vandeweyer et al., 2021).

For contaminants of group 2 (e.g., heavy metals such as cadmium and lead), whether or not the BSF-based product can safely be used as feed or fertilizer largely depends on the initial contaminant in the feedstock. Contamination of the BSF-based product can be avoided by not using the feedstock or dilution with non-contaminated material. However, when using common organic wastes such as kitchen, restaurant, or household wastes, the initial heavy metal concentration is at such a low level that the larvae do not exceed the thresholds set by governments despite a certain degree of bioaccumulation (Bessa et al., 2021; Bohm et al., 2022). At the current state of knowledge, no statement can be made regarding the risk and deactivation of prions.

Allergies

Both consumers of BSF-based products and operators could be prone to allergies by all BSF life stages. Most research focuses on insects as food and first tendencies show that shrimp-allergic patients are most likely at risk of food allergy to mealworm and other insects (Broekman et al., 2017; Guillet et al., 2022). However, ongoing research at University of Zurich also includes workers exposed to insects (handling, inhaling off-gas) and the results, expected in 2023, will be more relevant for the BSF sector. Because BSF companies work with biowaste that can include pathogens, strict health and safety SOPs including appropriate personal protective equipment (PPE) need to be in place, which also can protect against development of allergies.

History and development of the commercial BSF technology

The use of BSF larvae for the conversion of organic feedstocks into protein, fat, and frass has only been explored in more detail over the past two decades. Although the affinity of BSF larvae for organic waste has been known for some time, initial research focused on the suppression of houseflies in chicken houses or reducing the accumulation of chicken manure. With growing awareness of the finite nature of resources and the emerging idea of a circular economy, the technology eventually found its way into applied research and the construction of the first commercial waste treatment and protein production plants. Enterra in Canada (2007), Protix in the Netherlands (2009), and Agriprotein in South Africa (2009) were pioneers in this respect. As commercial interest increased, so did the activities of the research institutes. In the past ten years, the number of scientific publications on BSF has increased more than forty-fold (Figure 15). In addition, a diversification of research areas has been observed for some years. While early publications focused on bioconversion rate, life-history traits, and animal feeding experiments, more and more research groups specialize in other relevant topics such as pre-treatment, genetics, mating behavior, greenhouse gas emissions, or economic aspects.

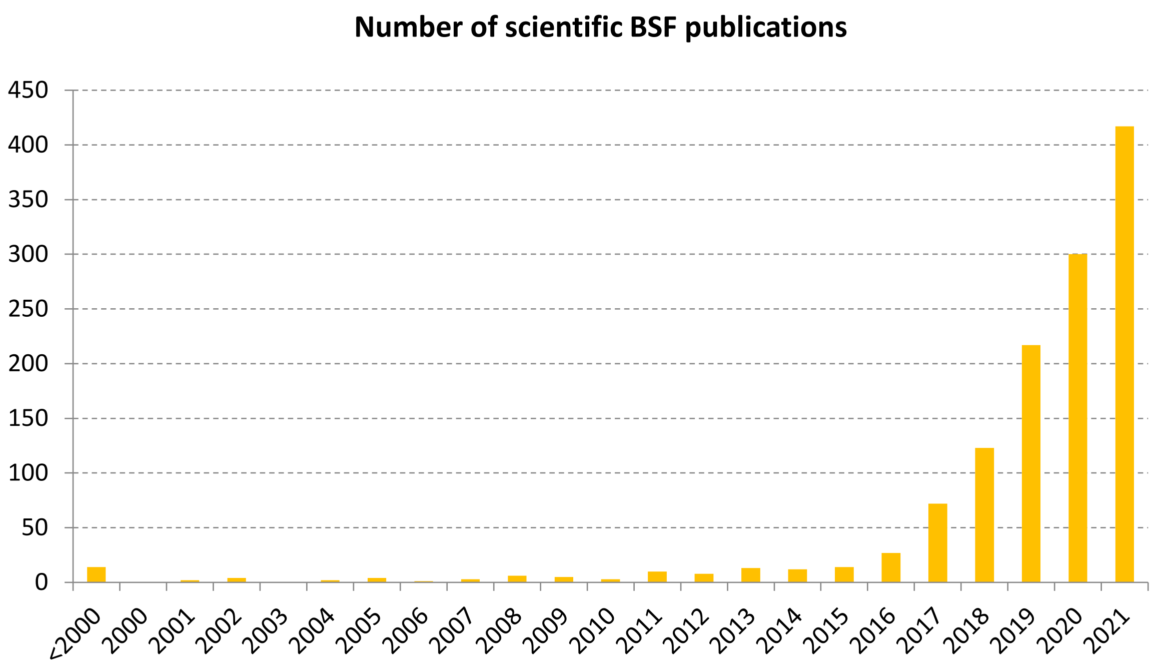


FIGURE 15: NUMBER OF PEER-REVIEWED PUBLICATIONS ON BLACK SOLDIER FLIES PER YEAR (RESULTS FROM SCOPUS SEARCH FOR "BLACK SOLDIER FLY" OR "HERMETIA ILLUCENS."

Over the years, three different types of BSF users have been formed. There is a large community, especially in North America, which operates BSF facilities in the backyard (Figure 16). This is mostly done without separate egg production/nursery and without commercial intentions. Often, these are self-built systems in which the migrating pupae are collected in a container and directly fed to chickens or fish.

FIGURE 16: EXAMPLE OF A SELF-MADE BSF COMPOST BIN (LEFT); MEDIUM-SCALE OPERATION IN KENYA (MIDDLE); SELF-HARVESTING FACILITY ON A FARM IN INDONESIA (RIGHT).

A second group operates smaller and medium-sized systems which they have built themselves and run with great passion (South-East Asia, Sub-Saharan Africa). The motivation is often a combination of circular economy activism, knowledge of the waste problem, and the demand for local animal feed, but also a commercial interest (Figure 16). Many of these facilities are operating at the lower end of their potential, either because of a lack of knowledge about how to operate optimally or because the enabling environment (access to waste, market, labor) is not right. With modest external funding used for consulting services and the construction of a pilot plant, the spread of such promising medium-sized plants could be stimulated.

The third group of BSF users are business-oriented entrepreneurs with a good education in engineering and/or economics. In most cases, the business plan for a mega plant is ready before the first fly has mated. Access to financial and human resources is possible thanks to personal contacts and good planning.

Luckily, all these three groups of practitioners can coexist, as they all occupy a different niche. Moreover, comparable to chicken farming or aquaculture, a market is developing for BSF products of different quantity, type, and quality as well as for equipment and services at all levels of BSF farming.

Intellectual properties

Since the beginning of the industry, companies and universities have been using patents to protect their inventions and intellectual properties and to prevent other players from entering their space. Espacenet, a database from the European Patent Office (EP), includes 1,908 patents related to BSF larvae rearing at the time of writing. However, 1,529 patents relate to patents in China, of which most are ungranted patent applications. The EP includes 29, of which 17 were granted. The US has 129 patents, of which around 50 were granted. South Korea has 75, Canada 55, Russia 31, Singapore 11, and the Netherlands 8 (it is not always easy to distinguish applications from granted patents). Some of the patents are held by Protix, Ynsect, Bühler Group, Nextalim, Hipromine, Innovafeed, and Enterra Feed. These patents relate to all aspects of a BSF facility listed below, and in particular, intellectual property, typically around BSF breeding (e.g., cages, attractant, water containers, collection of eggs, egg media, etc.) because these are technologies/processes that were brought about by the sector.

- General mass rearing of all life stages of the BSF
- Feedstock preparation
- Climate control
- Rearing container design
- Fly breeding cage design including egg collectors and oviposition attractant
- Extension of shelf life of young larval offspring
- Transporting of live insects
- Harvesting systems using the ability of BSF larvae to crawl off from the residue following completion of their feeding stage
- Production of BSF-based products for pets and livestock

Success factors for long-term financially viable operation

In the following section, the authors summarize some key success factors for a successful, long-term financially viable operation of a BSF facility. These are based on literature and the authors' own experience in the industry.

Feedstock

- Secure a reliable feedstock for the facility, ideally secured with offtake agreements. Preferably, try to tie feedstock producers into your business to ensure long-term feedstock supply (e.g., offtake agreements are often max 1-2 years whereas payback periods are much longer).
- Make realistic assumptions about feedstock cost, ideally through agreements. Globally, homogenous high-value feedstocks already have a use and therefore have a cost.
- Account for how transport costs can exceed feedstock costs or eat up revenues for waste treatment. When comparing feedstock costs/revenues, express feedstock costs including transport costs and considering dry mass (e.g. BSF larvae feedstock are typically >70% water) contribute to product yield and quality.
- Use representative BSF larvae feeding trials to determine facility design values and product qualities. Design values can vary with small changes in operational conditions, feedstock, and BSF strain.
- Ensure that you can legally use the feedstock for your target product.
- Do not think about the feedstock mixture leading to the highest growth but the mixtures with the optimal efficiency considering handling time, rearing cycle time, throughput, product quality, bioconversion rate, etcetera.

Technology

- Be creative. BSF facilities mostly combine devices and equipment that already exist in the agro-industrial sector. Consider equipment that is available locally and consider using/adapting technologies from other industries.
- Pick your battles. It is difficult to develop all technologies for a BSF facility yourself. Be smart about where it is useful to buy equipment and where it is worth developing/adapting your own.
- Understand that you get what you pay for. Do not expect magic results from cheap equipment (even though this can happen). The feedstock preparation, BSF larvae rearing, and parts of the product harvesting and processing environment involve highly corrosive, quickly damaged equipment that is cheap or of the wrong material. This includes the building housing the corrosive equipment.
- Follow standard engineering approaches (e.g., design based on desired product, available raw material).

- If possible, co-locate with inexpensive sources of energy (i.e., electricity and heat). Ideal is waste heat from incinerators or industrial processes. Operation of the HVAC as well as product drying requires large amounts of energy.

Market

- Understand your market and define what product you aim to produce. Define agreements with potential offtakes early on (e.g., naming products, rough product quality, tonnage).
- Make sure to allot enough time for product development with the client, especially if they are your first customer, because BSF-based products are relatively new.
- Understand what your customers expect from the product. For example, BSF larvae as pet food should not make pets sick and overweight and should be sustainable. In contrast, aquaculture and livestock farms expect high and steady growth of their animals with BSF larvae protein meal.
- Account for price sensitivity of agricultural markets (e.g., both for feed and fertilizer).
- Make sure that the products you produce are legal and you have all permits.
- Consider that the price you receive as a start-up when selling kilogram bags of product B2C cannot be transferred to a much larger production output.
- Consider cooperatives of small-scale farmers (if necessary to penetrate certain markets).
- Include stakeholders: farmers, politicians, private industry, and NGOs.

Team

- BSF rearing and breeding is a biological process. Invest in a team with a respective background. This will be indispensable especially when running into operational problems.
- Consider agriculture staff (e.g., plant and animal farming) in your production facility. They are familiar with working in farming environments such as BSF rearing/breeding.
- Consider existing training opportunities (e.g., online and offline resources).
- Aim to build a network with other BSF companies, insect and agricultural associations, and academics to advocate for your business and for exchange with operational issues.

Roadmap to a BSF facility

Depending on the treatment and production capacity, a BSF facility is a significant infrastructure project and general engineering principles from the food, agricultural, and energy space apply. Figure 17 shows a basic project cycle of a BSF facility that applies both for demo, pilot, and large-scale facilities.

- Demo facilities are small and showcase the general processes of a BSF facility. They are used to build up biological knowledge, attract initial investment, test feedstocks and produce first product, build up a small team, and network (e.g., veterinary offices, food and agricultural authorities, advisors).
- Pilot facilities should be designed based on the anticipated waste treatment and product of the final commercial facility. There can be different types of pilot plants. Veldkamp et al. (2021) distinguish all-purpose-pilot facilities and validation pilot facilities. All-purpose facilities are often legacy operations that have grown slowly as a patchwork of technologies from demo facilities. In contrast, validation pilot facilities are small versions of the commercial facility (Manzanares Rosenberg, 2022b). This means using the same feedstock and technology and producing the same product as in the commercial facility. They also have the same operational procedures. This ensures that knowledge generated in the pilot phase can be translated into the final commercial phase. However, companies may have to compromise this due to resource limitations regarding capex, opex, and space.
- Commercial facilities are several to several tens of times larger in size and treatment/production capacity than pilot plants. They should be designed based on the pilot phase and a rigorous engineering cycle for the desired end goal/product (e.g., waste treatment vs. product, type and quality of products), considering the legal requirements (i.e., product, emissions, labor, etc.).

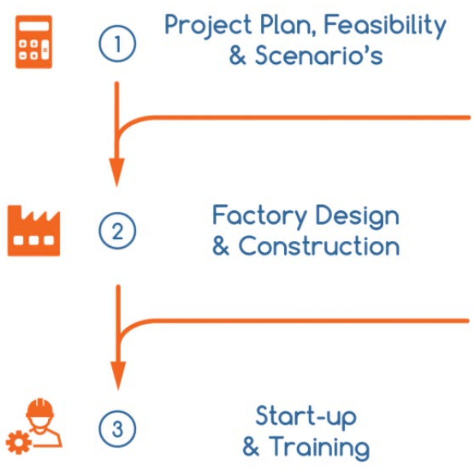


FIGURE 17: BASIC PROJECT CYCLE OF A BSF FACILITY (SOURCE: INSECTSYSTEMS).

In summary, commercial BSF facilities should be designed backwards from the anticipated commercial plant (Manzanares Rosenberg, 2022b). A typical engineering cycle includes pre-engineering, concept engineering, basic engineering, and engineering, procurement, and construction (EPC), followed by dry/wet commissioning, start-up, and ramp-up (Veldkamp et al., 2021). Times given below are for a large-scale facility treating tens or hundreds of tons of feedstock per day (assuming permitting in parallel to detailed engineering and procurement).

- Pre-engineering (3-6 months): Completion of a technical feasibility study and development of a project plan and upscaling plan. In this phase, it is important to provide broad project boundary conditions for location (e.g., labor cost, space availability), feedstock (e.g., type, cost, availability, and performance metrics), product, technology choice, and legal requirements (Shmulevich, 2021).

- Concept engineering, basic engineering, and detailed engineering (6-12 months): Main engineering of the facility. Development of engineering documents with detail increasing from concept (e.g., block flow diagram) to detailed engineering (e.g., piping and instrument diagram) including block flow diagram, mass balance, final technology choice, process flow diagram, capex list, route planning, operational manuals and equipment specifications, layout, and final cost estimates.

- Procurement, construction, commissioning, and start-up (6-18 months): Different project management models exist for execution of the project. A common form is EPC or EPCM where the procurement, construction, and commissioning of the facility are the responsibility of a contractor, meaning the contractor delivers a ready-to-operate facility.

- Start-up and ramp-up (6-18 months): Start-up is where the BSF company works on getting all processes up and running to the design capacity. The ramp-up period in BSF facilities is typically longer than that of other infrastructure projects because the BSF breeding has to be scaled up. In addition, sourcing feedstock several times that of the pilot facility can be challenging.

Other than scaling by making large steps given certain climatic and economic conditions (e.g., low labor costs, availability of space, consistent warm and humid climate), BSF facilities can also grow more organically by slowly increasing over time—for example, by slowly increasing the footprint, working hours, and number of crates and cages following the demand for waste treatment and product. This includes inefficiencies such as suboptimal layout and process flow and lack of economy of scale (e.g., feedstock preparation and product processing), but those may not be relevant in certain facility locations, particularly in low- and middle-income countries.

In contrast to five years ago, the market of technology and engineering providers has increased and most technology in a BSF facility is off-the-shelf equipment (see section "Service providers”). This also gives BSF companies and investors the choice of different models for realizing BSF facilities. These include:

1. Design and implement a BSF facility with a team of in-house and third-party engineers/contractors. Integrate technologies of several third-party providers. This may have a lower cost than the turnkey model but requires an in-house skilled team. No performance guarantees will be provided by technology providers and there may be overlapping/lacking responsibilities of technology providers at interfaces.

2. Design and implement a turnkey BSF facility from a one-stop shop (e.g., Bühler Group or Better Insect Solutions) including EPC. This model requires a smaller team on the BSF company’s side but likely has a higher cost for the one-stop show provider. The EPC can provide performance guarantees to the BSF company. The BSF company has one contact in case of technical problems.

3. Develop technologies and integrate with technologies of third-party providers. This is time consuming but can create a BSF company’s own IP that distinguishes it from its competitors. However, it is then important to define whether the company is a BSF technology or BSF production company. The insect industry is currently dynamic and fast and companies without a clear focus may find themselves overtaken by others or integrate into more consolidated competitors (Manzanares Rosenberg, 2022a).

4. Develop BSF facilities through partnership with existing BSF companies, potentially including engineering and EPC (e.g., Entogreen). This requires less knowhow and a smaller team on the BSF company’s side. However, the company may be locked into a partnership that can go sour and likely pays licensing fees and/or royalties.

Players in the BSF industry

Overview of the BSF market

Figure 18 shows the number of BSF companies globally. These were mapped using open-source information (e.g., reports, internet, authors' knowledge and network) at the time of writing this report. In total, 121 companies were identified. This covers all major companies based on production capacity but underestimates the total number as smaller companies and smallholder initiatives are not adequately covered. The company names per country with a website (if available) are included in Appendix A.

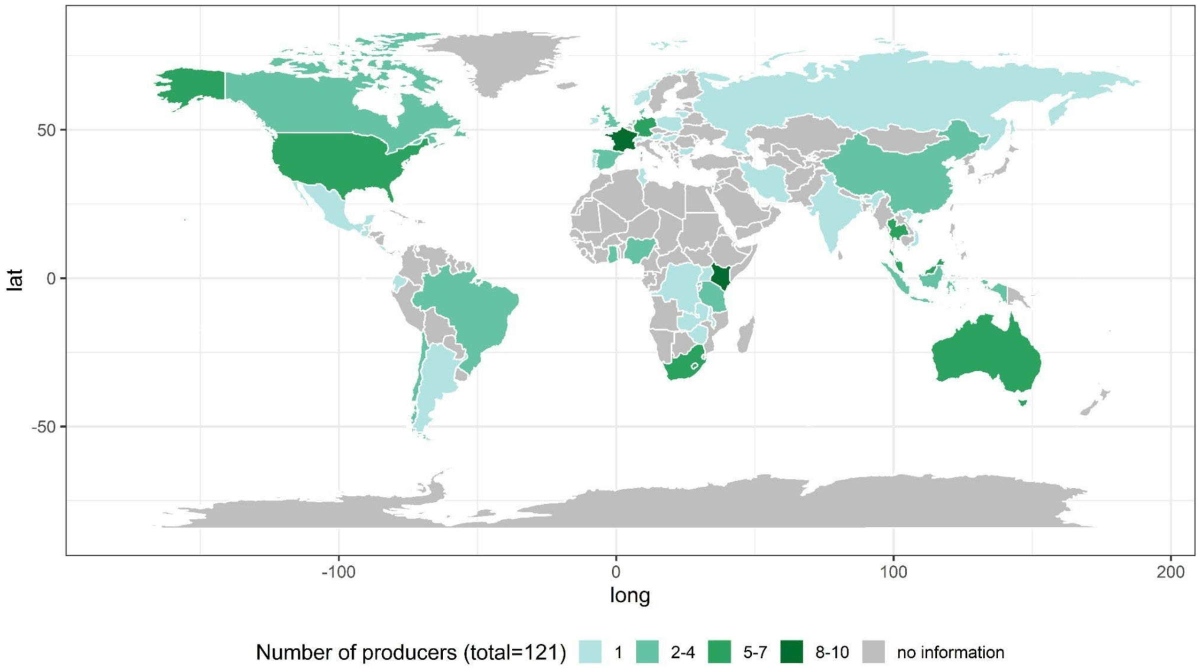


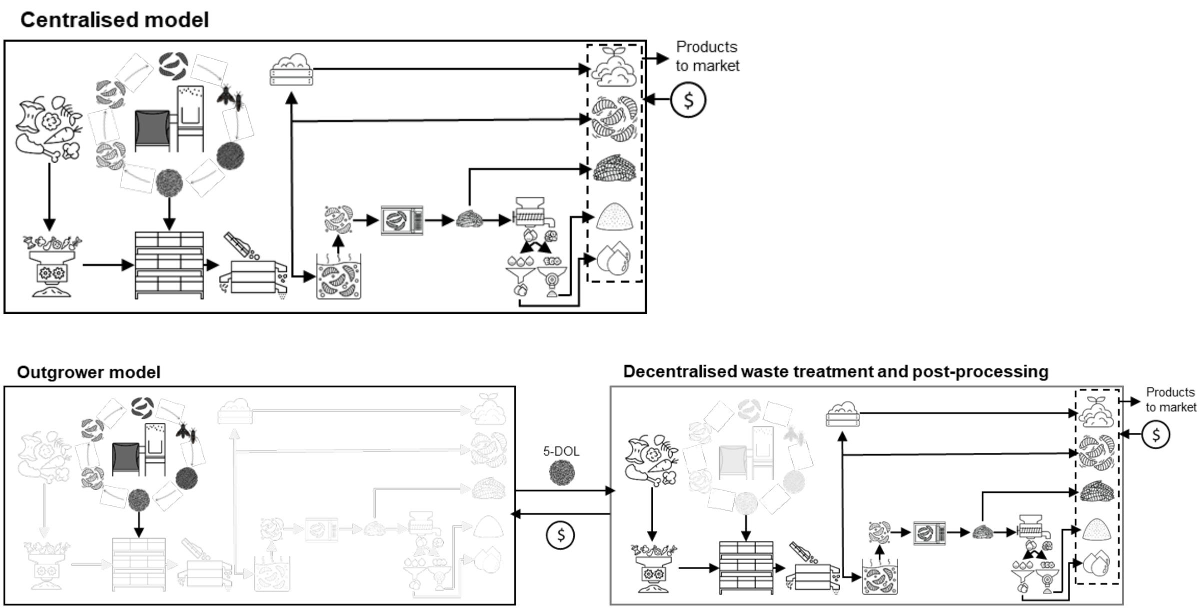
FIGURE 18: NUMBER OF BSF COMPANIES GLOBALLY (GOLD ADVISORY BASED ON APPENDIX A).

There are various different fields of activity in the BSF sector. The following section describes the different business models based on products and production setup. Short company profiles corresponding to the business models presented can be found in Appendix B. Development of the company profiles was based on own knowledge, interviews with companies, company websites, Crunchbase (regarding investments) and other websites, particularly Feed Navigator and All About Feed. Because investments and investors are not very transparent, the reason and motivation of the investment could not be provided. In general, large investments (e.g., > 5 million in Asia and Africa, > 20 million in Europe and North America) are for the establishment of one or more large-scale BSF facilities.

Different production models

Similar to farming of other beneficial animals such as poultry or bees (where the outgrower model is common), different business models can be distinguished based on the production setup. They are summarized for BSF in Figure 19.

- In the centralized model, all units of a BSF facility are in one location. Feedstock from one or multiple producers are brought to the BSF facility.
- In the "outgrower" model, the BSF reproduction to produce young larvae offspring for waste treatment is located separately from rearing and product harvesting and processing. BSF eggs or young larvae are transported from BSF breeding to different rearing locations. In this model, the rearing of BSF larvae may be done by a different company than the BSF reproduction. In this case, the company buys eggs or larvae offspring from the reproduction company.
- The outgrower model with centralized processing is similar to the outgrower model. The difference is that the harvested larvae are returned to the outgrower (or another company) for processing. Because product processing equipment (e.g., drying and defatting) is costly, having a centralized processing location can reduce overall cost. However, transport costs for returning the BSF larvae to the processing location must also be considered.



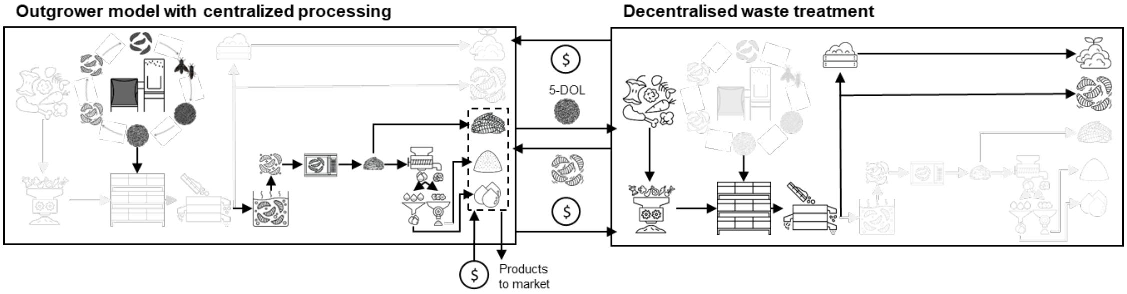


FIGURE 19: THREE DIFFERENT PRODUCTION MODELS CONSIDERED BY EAWAG: CENTRALIZED MODEL, OUTGROWER MODEL, AND OUTGROWER MODEL WITH CENTRALIZED PRODUCT PROCESSING (Grau et al., 2022).

Business model: Animal feed production

The motivation of this business model is quality and sustainability. Benchmarks for quality and sustainability are fishmeal or soy meal. These feed ingredients are associated with high negative environmental impacts (e.g., biodiversity loss through overfishing, deforestation to grow soy) and these impacts are expected to further increase with the predicted population growth, especially in low-income countries. Because the feedstock to grow BSF larvae has a large influence on process performance and product quality and reliability, companies with this business model typically use homogenous, high-value organic byproducts. These may include brewers' spent grain, residues from food processors, residues from the fruit juice industry, or other organic by-products from the food or agricultural sector.

Business model: Waste management

By nature, BSF larvae grow on a large variety of biowastes, including feedstocks such as animal manure, municipal organic solid waste (i.e., household organic waste), and food wastes (e.g., restaurant, market, hotel, and kitchen waste). BSF larvae convert biowastes into insect biomass and reduce the waste mass and volume in the order of 50-85% (based on dry and wet mass, depending on drying out of the waste material). In addition, the biowaste is turned into a compost-like residue and pathogens can be reduced. In this business model, companies use this ability with a focus on reducing biowaste mass and volume and treating waste. Companies can produce the same products (i.e., live larvae, protein meal, fat, and frass/compost) as companies focusing on feed production. However, key differences between the business models include:

- *Revenues from treating biowastes*: Companies focusing on animal feed production typically pay for their feedstocks. In contrast, BSF companies focusing on waste management are often (partially) paid for treating biowaste.

- *Higher environmental, social, and economic impact*: Companies that treat biowaste that is currently poorly managed and therefore pollutes the environment contribute to environmental and public health and thereby promote economic development.
- *Potentially lower bioconversion performance and higher variability*: Because biowastes can be low in nutrients and high in digestible fibers that are hard for BSF larvae to digest, process performance can be lower with this business model than when high-value agri-food byproducts are used.
- *Potentially lower product value*: Biowastes are intrinsically variable in moisture content, nutrients, and physical properties. This will typically result in products having a higher variability in key parameters, such as fat and protein content (for live and dried larvae, as well as protein meal), fatty acid composition (for fats), and nitrogen, phosphorus, and potassium (for frass/compost). Such a variability is typically undesired and may reduce the achievable product price.
- *More demand for technology selection, design, and operation*: Because biowastes are variable, selection and design of appropriate technology is more challenging, and operation may put more demand on machinery (e.g., pumping high-viscosity feedstocks). In general, operations need to be more flexible (e.g., HVAC parameters, harvesting time) to compensate for the variable growth, waste reduction, bioconversion performance, water evaporation, and heat production.
- *Higher requirements on product processing and quality control to ensure safe products*: Biowastes typically include microbial and chemical contaminants that can be partially found in the products. Even though some microbes and aflatoxins are being reduced, post-processing (e.g., drying at a certain temperature) is required in addition to analyses of each product batch for indicator parameters. Heavy metals such as cadmium and lead and pathogens are of special concern, but the fate of chemicals such as pharmaceuticals and pesticides is poorly studied.

In summary, producing high-value products on variable biowastes is a lot more challenging. However, this business model delivers other financial flows and on the sustainability claims made by the industry.

Business model: Young larval offspring

In recent years, the BSF sector has seen initiatives to separate production of BSF offspring (i.e., eggs, neonates, or 5DOLs) from the main bioconversion process on byproducts and wastes (i.e., approx. 5DOL to harvest). This is similar to farming of other animals (e.g., pigs, poultry) where specialized breeders provide young animal offspring to farmers for rearing of mature animals. This has similarities to the outgrower schemes in livestock farming where young animals are provided by specialized companies. Separating the value chain also gives opportunities to move the labor-intensive reproduction to countries with lower labor costs and favorable climates (i.e., (sub)tropical areas in Asia, Africa, and South America).

This business is not yet very established and many players are currently still running their own breeding and nurseries. No industrial-scale example exists where a third-party breeding company delivers all young offspring. We expect this to change in the future. Industrial-scale projects require large amounts of offspring (e.g., 5-10 kg of eggs/day) and no breeding company is currently (over)producing these quantities. Consequently, bioconversion companies and breeding companies need to scale together in parallel. No data is available on the financial viability of breeding companies, but they likely have considerable economies of scale, especially when delivering to multiple companies in one region (e.g., Europe, North America).

Advantages to the bioconversion company include lower initial capex because the nursery infrastructure is outsourced to the breeding company. In addition, the bioconversion company does not need to acquire the specialized knowledge of reliably producing offspring which could lead to a quicker scaleup/expansion. BSF are a lot less robust in their fly and young larval stages. Reproduction of flies, laying of fertile eggs, hatching of eggs, and the first few days of the larval life stage are a lot more difficult to deal with than the main bioconversion process. A disadvantage for the bioconversion company is a dependency on the breeding company. Challenges for the BSF breeding companies can include the survival rate of the young larvae during transport across the globe and legal obstacles (import of live material). There need to be clear agreements on who covers disruptions in the operation of the bioconversion company in case of decreasing insect fitness or interrupted supply chains, even though the latter seems to be resolved by recent advancements in increasing the shelf life of offspring.

Business model: High-value products

Outputs of most BSF facilities are live, frozen, or dried larvae, protein meal or fats, and frass or compost. These outputs are raw materials for the formulation of animal feeds by farmers or animal feed or pet food companies. However, companies in this business model focus on creating more value from the frass or larval products by targeting high-value markets (e.g., chitin, chitosan, melanin, pharmaceutical, cosmetics, or technical applications).

Business model: Smallholder farmer

From the beginning, the BSF technology attracted the attention of smallholder farmers and private individuals who saw a way to dispose of household waste with little effort and use it to produce feed for their chickens (Chia et al., 2019). Many such systems are based on the principle that the pre-pupae leave the waste in search of a dry place to pupate and can thus be harvested relatively easily (Figure 20). These systems are similar to backyard composting and work relatively well on a smaller scale, but are not designed for commercial production of larvae.

Further development of such systems can be observed especially in Sub-Saharan Africa (mainly Kenya) and Indonesia. Here, some entrepreneurs offer training in BSF farming and thus train farmers in BSF cultivation and waste management. In most cases, however, the farmers are overburdened with the tasks, which leads to inadequate operation of the facilities (infestation with vinegar flies, unsatisfactory bioconversion, high labor input, etc.) (Figure 21).

Future efforts in R&D could lead to a simplified BSF system that allows operation requiring little labor and technical knowledge, comparable to beekeeping or chicken farming.

FIGURE 20: SELF-HARVESTING "LARVERO" IN COSTA RICA.

FIGURE 21: ABANDONED BSF FACILITY ON A FARM IN KENYA DUE TO LACK OF WASTE AND SMALL LARVAE.

Technology and service providers

Technology providers

BSF facilities require considerable technology, including feedstock preparation (e.g., maceration, mixing), feedstock loading/unloading, HVAC (e.g., ventilation, heating/cooling), counting of larval offspring, trays, or beds, breeding cages, and larval and frass separation and processing. Recent years have seen the emergence of several companies providing standalone units among the BSF valorization chain such as container-based waste treatment units or automated nurseries. There are also several companies providing planning, design, and operational support.

Find below a few examples:

Open-source equipment instructions: Aside from the commercial players listed below, a wide range of open-source resources are available on the internet. Examples include:

- "Practical knowhow on BSF-processing" by the Swiss Federal Institute of Aquatic Science and Technology (Eawag). This includes a guide to design, build, and operate a 5-ton feedstock/day facility in tropical climates, including a financial model.
- Several groups/accounts on Facebook, LinkedIn, and Instagram.

- "Technical handbook of domestication and production of diptera Black Soldier Fly (BSF) Hermetia illucens, Stratiomyidae" by Carusco et al. (2013).
- Discussion forums such as Reddit.

Chapul Farms: Chapul Farms is a US-based agriculture project development company that designs, builds, and operates commercial-scale BSF larvae facilities.

BEF Biosystems: BEF Biosystems is based in Northern Italy and sells modular small- to medium-scale (e.g., several tons/day) BSF facilities. They have been founded out of the need to have smaller scale BSF facilities because of lower regulatory restrictions and faster project implementation.

Better Insect Solutions: Better Insect Solutions is a collection of business units of the Big Dutchman Group. Big Dutchman is one of the largest providers of turnkey poultry and pig farms. They are headquartered in Northern Germany. Better Insect Solutions is headed by SKOV, a premium company for animal farm climate systems headquartered in Denmark. Additional members are Big Dutchman for feedstock preparation and dosing and Inno+ for heat recovery and air cleaning. Better Insect Solutions' ambition is to become a turnkey provider of BSF facilities. They already adapted their climate systems for all life stages of the BSF and developed their own crates. A breeding system is currently in development. They develop their business closely with the Enorm Biofactory in Denmark, which is currently upscaled to an industrial size.

Better Origin: UK-based Better Origin sells containerized BSF larvae rearing facilities using artificial intelligence.

Bühler Insect Technology Solutions: Bühler based in Switzerland provides turnkey BSF facilities as an EPC company. Their scope includes all aspects, excluding BSF breeding. Their BSF facilities include their own equipment (especially on larvae and frass separation and insect processing) and equipment of third-party providers. Bühler is therefore currently one of the few players that gives performance over the entire BSF facility. Bühler was EPC and provided most equipment for the Protix BSF facility in the Netherlands. An additional facility for rearing of mealworms is under construction in France for Agronutris.

Entomoventures: Entomoventures works on digital solutions for BSF facilities.

Evo Conversion Systems: The founding of Evo is associated with Jefferey Tomberlin, one of the most influential academic figures of the BSF industry. Evo Conversion Systems provides consultancy service and sells equipment, mostly manufactured in China for medium-scale facilities (several tons to 50 tons/day of feedstock, depending on labor costs). Unique is Evo's own cage, crate, eggie, and light company.

GEA, Celitron, and Alfa Laval: These companies are examples of providers of wet rendering lines for industrial-scale larval processing. A wet rendering line separates larvae into protein meal, fat, and stick water. Stick water typically requires wastewater treatment.

InsectoCycle: InsectoCycle sells a cage that combines rearing for breeding (i.e., 5DOL to pupae), pupae incubation, and the fly stage in one system. InsectoCycle's aim is thereby to reduce the number of staff and overall operational costs. It is one of the few third-party industrial-scale breeding solutions (e.g., 10 kg eggs/day). The cage consists of two parts: a dark cage in the back and a light cage in the front. Each week, a stack of crates with young larvae is placed on sufficient high-quality feedstock and placed into the cage at the front end. At the same time, a stack of crates with hatched/used pupae is pushed out at the opposite end. Flies that emerge in the dark part of the cage fly to the light cage in the front. Full egg trays can be harvested as a product. A large part of the otherwise technically demanding egg production is thus greatly simplified. A possible reduction in egg production per larva due to automation is compensated for by the reduced labor costs.

Insect Engineers: Insect Engineers was founded out of Mush Comb, a leading provider of equipment for farming of mushrooms. Insect Engineers, based in the Netherlands, adapted this equipment to farming of BSF larvae. Next to Nasekomo, they are one of the few companies not working with crates. Instead, they have the bioconversion process on 30-40 long beds.

Livin Farms: Livin Farms offers medium-scale producers of organic byproducts (5-20 tons/day) an on-site solution that is tailored to the customer's specific feedstock. The young larvae can be supplied by Livin Farms, which greatly simplifies the operation of the actual facility and should ensure that the facility can be operated by the client itself. Livin Farms operates a demo facility in Vienna that can be visited by potential clients.

Manna Insect: The Finnish company Manna Insect sells containerized BSF bioconversion for homogenous feedstocks such as potatoes. They have a partnership for production of these containers in India. Current project locations include Kenya.

Nasekomo: Nasekomo is a Bulgarian BSF producer and technology provider. They have a proprietary technology BSF bioconversion technology that is based on vertically stacked beds instead of the conventional crate system.

Reinartz: German-based Reinartz sells defatting presses for dry rendering of larvae, producing protein meal and fats.

Soldier Fly Technologies: Soldier Fly Technologies is based in California and provides consulting services (e.g turnkey facility plans, exported operational support) and technology licensing.

VDL Insect Systems: Durch VDL Insect Systems is an industrial and manufacturing company that sells equipment for BSF facilities including feedstock preparation, crates and logistics, HVAC, and processing.

Other companies include: Viscon (crate handling), Weda (feedstock preparation), Beekenkamp (crates), Russell (vibrating sieves), Sairem (microwave drying), Monts (dryer), Vogelsang (waste processing), Entomal (crates, stacking, entire systems), Yellowstar Trading Limited (waste processing, harvesting, drying and specialized HVAC equipment), Royal Dutch Kusters (product separation) and Metafly (waste-to-BSFL modular unit).

Service providers

In addition to the manufacturers and distributors of equipment, there is a market of service providers who support the BSF sector with their specific knowledge. This can include the planning and dimensioning of plants as well as support during construction or the training of personnel.

Gold Advisory: Gold Advisory supports start-ups, companies, and investors in scaling BSF larvae bioconversion for waste management and feed production. They complete feasibility studies and concept engineering, feedstock mapping and formulation, techno-financial comparisons and due diligence, operational and R&D support, and development of R&D strategies.

Eclose GmbH: Eclose's service focuses on consulting and guiding operators of non-automated BSF facilities worldwide, conducting feasibility studies, and supervising and advising the R&D projects of academic research institutes, universities, or NGOs.

InsectProjects: InsectProjects specializes in the development and implementation of complete BSF production facilities, providing project development support, design, engineering, execution plans, project management, operation support, and operation protocols.

Hermetia Tech: Hermetia Tech is based on Java in Indonesia and specializes in the training and consulting services for rearing BSF on organic wastes. Since 2017, Hermetia Tech has been implementing BSF technology and improving existing systems creatively, as well as providing training to Indonesian and international clients.

Proteinmaster: Kenyan-based Proteinmaster provides offline training to enable production of BSF-based products for feed. They have a BSF facility in Huruma near Nairobi where they rear BSF and provide training.

ProEnto: Based in the Netherlands, ProEnto provides business development support for BSF facilities by providing planning, operational support, and insect breeding technology. They especially have experience in Latin America and Africa.

Christof Industries: Christof Industries is an engineering company headquartered in Austria. They provide EPC of BSF facilities. They had a partnership with Agriprotein and have since then been involved in the BSF sector.

References

Abro, Z., Kassie, 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.

Alagappan, S., Rowland, D., Barwell, R., Mantilla, S. M. O., Mikkelsen, D., James, P., Yarger, O., & Hoffman, L. C. (2022). Legislative landscape of black soldier fly (Hermetia illucens) as feed. *Journal of Insects as Food and Feed*, *8*(4), 343–355.

Anglo American. (2022). *Anglo American invests in Sanergy organic waste upcycling (accessed: 31.10.2022)*. https://www.angloamerican.com/media/press-releases/2022/28-06-2022

Araujo, P., Tefera, T., Breivik, J., Abdulkader, B., Belghit, I., & Lock, E. J. (2022). A rapid acid hydrolysis method for the determination of chitin in fish feed supplemented with black soldier fly (Hermetia illucens) larvae. *Heliyon*, *8*(6), e09759.

Barragán-Fonseca, K. B. (2018). *Flies are what they eat: Tailoring nutrition of Black Soldier Fly (Hermetia illucens) for larval biomass production and fitness*. Wageningen University & Research (WUR).

Barragán-Fonseca, K. B., Dicke, M., & van Loon, J. J. A. (2017). Nutritional value of the black soldier fly (Hermetia illucens L.) and its suitability as animal feed – a review. *Journal of Insects as Food and Feed*, *3*(2), 105–120.

Beniers, J. J. A., & Graham, R. I. (2019). Effect of protein and carbohydrate feed concentrations on the growth and composition of black soldier fly (Hermetia illucens) larvae. *Journal of Insects as Food and Feed*, *5*(3).

Bertinetti, C., Samayoa, A. C., & Hwang, S. Y. (2019). Effects of Feeding Adults of Hermetia illucens (Diptera: Stratiomyidae) on Longevity, Oviposition, and Egg Hatchability: Insights Into Optimizing Egg Production. *J Insect Sci*, *19*(1).

Bessa, L. W., Pieterse, E., Marais, J., Dhanani, K., & Hoffman, L. C. (2021). Food Safety of Consuming Black Soldier Fly (Hermetia illucens) Larvae: Microbial, Heavy Metal and Cross-Reactive Allergen Risks. *Foods*, *10*(8). https://doi.org/10.3390/foods10081934

Biancarosa, I., Liland, N. S., Biemans, D., Araujo, P., Bruckner, C. G., Waagbø, R., Torstensen, B. E., Lock, E.-J., & Amlund, H. (2017). Uptake of heavy metals and arsenic in black soldier fly (Hermetia illucens) larvae grown on seaweed-enriched media. *Journal of the Science of Food and Agriculture*, *98*(6), 2176–2183.

Bogdan, G., Ioan, S. D., Mihai, S., Elena, M. L., Vasile, M. D., & Mihaela, B. A. (2022). Particularities of the Hermetia illucens (L.) (Diptera: Stratiomyidae) Ovipositing Behavior: Practical Applications. *Insects*, *13*(7).

Bohm, K., Hatley, G. A., Robinson, B. H., & Gutiérrez-Ginés, M. J. (2022). Black Soldier Fly-based bioconversion of biosolids creates high-value products with low heavy metal concentrations. *Resources, Conservation and Recycling*, *180*.

Bosch, G., van Zanten, H. H. E., Zamprogna, A., Veenenbos, M., Meijer, N. P., van der Fels-Klerx, H. J., & van Loon, J. J. A. (2019). Conversion of organic resources by black soldier fly larvae: Legislation, efficiency and environmental impact. *Journal of Cleaner*

Production, *222*, 355–363.

Bosch, Guido, Zhang, S., G.A.B., D., & Hendriks, W. H. (2014). Protein quality of insects as potential ingredients for dog and cat foods. *Journal of Nutritional Science*, *3*(29), 1–4.

Broekman, H., Knulst, A. C., de Jong, G., Gaspari, M., den Hartog Jager, C. F., Houben, G. F., & Verhoeckx, K. C. M. (2017). Is mealworm or shrimp allergy indicative for food allergy to insects? *Mol Nutr Food Res*, *61*(9).

Bryan, G. & C. (2022). *Insects as feed. Alternative proteins – the trend towards meat, dairy and feed substitutes.*

Business News Australia. (2022). *Bardee plans 'mega' organic fertiliser facility in Melbourne after carbon certification (accessed: 31.10.2022)*. https://www.businessnewsaustralia.com/articles/bardee-plans--mega--organic-fertiliser-facility-in-melbourne-after-carbon-certification.html

Chia, S. Y., Tanga, C. M., van Loon, J. J., & Dicke, M. (2019). Insects for sustainable animal feed: inclusive business models involving smallholder farmers. *Current Opinion in Environmental Sustainability*, *41*, 23–30.

De Smet, J., Wynants, E., Cos, P., & Van Campenhout, L. (2018). Microbial community dynamics during rearing of black soldier fly larvae (Hermetia illucens) and its impact on exploitation potential. *Applied and Environmental Microbiology*, *84*(9).

Diener, S., Zurbrügg, C., & Tockner, K. (2009). Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. *Waste Management & Research*, *27*(6), 603–610.

Dortmans, B., Diener, S., Verstappen, B., & Zurbrügg, C. (2021). *Black Soldier Fly Biowaste Processing*. Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Elissen, H. J. H., Hol, S., & van der Weide, R. (2019). *Methane production from insect, worm and mushroom waste streams and combinations*. Wageningen University & Research.

Ermolaev, E., Lalander, C., & Vinnerås, B. (2019). Greenhouse gas emissions from small-scale fly larvae composting with Hermetia illucens. *Waste Management*, *96*, 65–74.

Facchini, E., Shrestha, K., van den Boer, E., Junes, P., Sader, G., Peeters, K., & Schmitt, E. (2022). Long-Term Artificial Selection for Increased Larval Body Weight of Hermetia illucens in Industrial Settings. *Frontiers in Genetics*, *13*, 1–9.

Food and Agriculture Organization of the United Nations (FAO). (1997). *Animal Feeding and the Safety of Food (Report of an FAO Expert Consultation)*.

Food and Agriculture Organization of the United Nations (FAO). (2020). *The state of world fisheries and aquaculture*.

Freel, T. A., McComb, A., & Koutsos, E. A. (2021). Digestibility and safety of dry black soldier fly larvae (BSFL) meal and BSFL oil in dogs. *Animal Science*, 1–18.

Fuhrmann, A., Wilde, B., Conz, R. F., Kantengwa, S., Konlambigue, M., Masengesho, B., Kintche, K., Kassa, K., Musazura, W., Späth, L., Gold, M., Mathys, A., Six, J., & Hartmann, M. (2022). Residues from black soldier fly (Hermetia illucens) larvae rearing influence the plant-associated soil microbiome in the short term. *Frontiers in Microbiology*, *13*, 1–19.

Giunti, G., Campolo, O., Laudani, F., & Palmeri, V. (2018). Male courtship behaviour and potential for female mate choice in the black soldier fly Hermetia illucens L. (Diptera: Stratiomyidae). *Entomologia Generalis*, *38*, 29–46.

Gold, M., Cassar, C. M., Zurbrügg, C., Kreuzer, M., Boulos, S., Diener, S., & Mathys, A. (2020). Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Management*, *102*, 319–329.

Gold, M., Ireri, D., Zurbrügg, C., Fowles, T., & Mathys, A. (2021). Efficient and safe substrates for black soldier fly biowaste treatment along circular economy principles. *Detritus*, *16*, 31–40.

Gold, M., Tomberlin, J. J. K., Diener, S., Zurbrügg, C., & Mathys, A. (2018). Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: A review. *Waste Management*, *82*, 302–318.

Gold, M., von Allmen, F., Zurbrügg, C., Zhang, J., & Mathys, A. (2020). Identification of bacteria in two food waste black soldier fly larvae rearing residues. *Frontiers in Microbiology*, *11*, 2897.

Grau, M. G. P., Dortmans, B. M. A., Egger, J., Virard, G., & Zurbrügg, C. (2022). Modelling the financial viability of centralised and decentralised black soldier fly larvae waste processing units in Surabaya, Indonesia. *Journal of Insects as Food and Feed*, 1–14.

Guillet, C., Martin, O. Y., Meincke, C., Joerg, L., & Schmid-Grendelmeier, P. (2022). Part II: Insect allergies—Inhalation and ingestion. *Allergo Journal International*.

Heussler, C. D., Walter, A., Oberkofler, H., Insam, H., Arthofer, W., Schlick-Steiner, B. C., & Steiner, F. M. (2019). Influence of three artificial light sources on oviposition and half-life of the Black Soldier Fly, Hermetia illucens (Diptera: Stratiomyidae): Improving small-scale indoor rearing. *PLoS ONE*, *14*(12), 40–45.

Higa, J. E., Ruby, M. B., & Rozin, P. (2021). Americans' acceptance of black soldier fly larvae as food for themselves, their dogs, and farmed animals. *Food Quality and Preference*, *90*.

Holmes, L. A., VanLaerhoven, S. L., & Tomberlin, J. K. (2017). Photophase Duration Affects Immature Black Soldier Fly (Diptera: Stratiomyidae) Development. *Environ Entomol*, *46*(6), 1439–1447.

Huis, A. van, & Tomberlin, J. K. (2016). *Insects as food and feed: from production to consumption.* Wageningen Academic Publishers.

Indexmundi. (2022a). *Coconut oil price (accessed: 31.10.2022)*. https://www.indexmundi.com/commodities/?commodity=coconut-oil

Indexmundi. (2022b). *Monthly fishmeal price (accessed: 31.10.2022)*. https://www.indexmundi.com/commodities/?commodity=fish-meal

Indexmundi. (2022c). *Soybean oil price (accessed: 31.10.2022)*. https://www.indexmundi.com/commodities/?commodity=soybean-oil

International Platform of Insects for Food and Feed (IPIFF). (2022). *Guide on Good Hygiene Practices for European Union (EU) producers of insects as food and feed*.

Ipema, A. F., Gerrits, W. J. J., Bokkers, E. A. M., Kemp, B., & Bolhuis, J. E. (2020). Provisioning of live black soldier fly larvae (Hermetia illucens) benefits broiler activity and leg health in a frequency- and dose-dependent manner. *Applied Animal Behaviour Science*, *230*.

Joly, G., & Nikiema, J. (2019). Global experiences on waste processing with black soldier fly (Hermetia illucens): From technology to business. In *Resource Recovery and Reuse* (Vol. 2019, Issue 16). International Water Management Institute (IWMI).

Kaya, C., Generalovic, T. N., Ståhls, G., Hauser, M., Samayoa, A. C., Nunes-silva, C. G., Roxburgh, H., Wohlfahrt, J., Ewusie, E. A., Kenis, M., Hanboonsong, Y., Orozco, J., Carrejo, N., Nakamura, S., Gasco, L., Rojo, S., Tanga, C. M., Meier, R., Rhode, C., … Sandrock, C. (2021). *Global population genetic structure and demographic trajectories of the black soldier fly , Hermetia illucens*. 1–22.

Klammsteiner, T., Turan, V., Fern, M., Oberegger, S., & Insam, H. (2020). Suitability of Black Soldier Fly Frass as Soil Amendment and Implication for Organic Waste Hygienization. *Agronomy*, *10*(10), 1578.

Lähteenmäki-Uutela, A., Marimuthu, S. ., & Meijer, N. (2021). Regulations on insects as food and feed: a global comparison. *Journal of Insects as Food and Feed*, *7*(5), 849–856.

Lalander, C., Diener, S., Magri, M. E., Zurbrugg, C., Lindstrom, A., & Vinneras, B. (2013). Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens) - From a hygiene aspect. *Science of the Total Environment*, *458–460*, 318–458.

Lalander, C., Diener, S., Zurbrügg, C., & Vinnerås, B. (2019). Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (Hermetia illucens). *Journal of Cleaner Production*, *208*, 211–219.

Lalander, C., Nordberg, Å., & Vinnerås, B. (2018). A comparison in product-value potential in four treatment strategies for food waste and faeces - assessing composting, fly larvae composting and anaerobic digestion. *GCB Bioenergy*, *10*(2), 84–91.

Lalander, C., Senecal, J., Gros Calvo, M., Ahrens, L., Josefsson, S., Wiberg, K., & Vinnerås, B. (2016). Fate of pharmaceuticals and pesticides in fly larvae composting. *Science of the Total Environment*, *565*, 279–286.

Li, L., Wang, Y., & Wang, J. (2016). Intra-puparial development and age estimation of forensically important Hermetia illucens (L.). *Journal of Asia-Pacific Entomology*, *19*(1), 233–237.

Liu, Z., Minor, M., Morel, P. C. H., & Najar-rodriguez, A. J. (2018). Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) Larvae. *Environmental Entomology*, *47*(6), 1609–1617.

Manzanares Rosenberg, A. (2022a). *Insect start-ups: What is the plan? (accessed: 31.10.2022)*. https://www.linkedin.com/pulse/insect-start-ups-what-plan-alvaro-manzanares-rosenberg/

Manzanares Rosenberg, A. (2022b). *Why an insect pilot plant? (accessed: 31.10.2022)*. https://www.linkedin.com/pulse/why-insect-pilot-plant-alvaro-manzanares-rosenberg/

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

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., & Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, *14*, 1–8.

Nakimbugwe, D., Ssepuuya, G., Male, D., Lutwama, V., Mukisa, I. M., & Fiaboe, K. K. M. (2020). Status of the regulatory environment for utilization of insects as food and feed in Sub-Saharan Africa-a review. *Critical Reviews in Food Science and Nutrition*, *61*(9), 1–10.

Niermans, K., Meyer, A. M., den Hil, E. F. H. van, van Loon, J. J. A., & van der Fels-Klerx, H. J. (2021). A systematic literature review on the effects of mycotoxin exposure on insects and on mycotoxin accumulation and biotransformation. *Mycotoxin Research*, *37*(4), 279–295.

Pang, W., Hou, D., Chen, J., Nowar, E. E., Li, Z., Hu, R., Tomberlin, J. K., Yu, Z., Li, Q., & Wang, S. (2020). Reducing greenhouse gas emissions and enhancing carbon and nitrogen conversion in food wastes by the black soldier fly. *Journal of Environmental Management*, *260*, 110066.

Parodi, A., De Boer, I. J. M., Gerrits, W. J. J., Van Loon, J. J. A., Heetkamp, M. J. W., Van Schelt, J., Bolhuis, J. E., & Van Zanten, H. H. E. (2020). Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing – A mass balance approach. *Journal of Cleaner Production*, *271*, 122488.

Parodi, A., Gerrits, W. J. J., Van Loon, J. J. A., De Boer, I. J. M., Aarnink, A. J. A., & Van Zanten, H. H. E. (2021). Black soldier fly reared on pig manure: Bioconversion efficiencies, nutrients in the residual material, greenhouse gas and ammonia emissions. *Waste Management*, *126*, 674–683.

Peguero, D. A., Gold, M., Vandeweyer, D., Zurbrügg, C., & Mathys, A. (2021). A review of pretreatment methods to improve agri-food waste bioconversion by black soldier fly larvae. *Frontiers in Sustainable Food Systems*, *5*.

Perez, S., & Wertz, J.-L. (2022). *Chitin and Chitosans in teh Bioeconomy*. CRC Press Taylor & Francis Group.

Purschke, B., Scheibelberger, R., Axmann, S., Adler, A., & Jäger, H. (2017). Impact of substrate contamination with mycotoxins, heavy metals and pesticides on growth performance and composition of black soldier fly larvae (Hermetia illucens) for use in the feed and food value chain. *Food Additives & Contaminants: Part A*, *34*(8), 1410–1420.

Rabobank. (2021). *No Longer Crawling : Insect Protein to Come of Age in the 2020s (exclusively for Rabobank clients)*. *

Reinartz. (2021). *Reinartz Research: Insect market prices (internal report shared with consultants)*.

Rodrigues, D. P., Ameixa, O. M. C. C., Vázquez, J. A., & Calado, R. (2022). Improving the Lipid Profile of Black Soldier Fly (Hermetia illucens) Larvae for Marine Aquafeeds: Current State of Knowledge. *Sustainability*, *14*(11).

Rozkosny, R. (1982). A Biosystematic Study of the European Stratiomyidae (Diptera), Volume I. In *Series Entomologica* (Vol. 1).

Sandrock, C., Leupi, S., Wohlfahrt, J., Kaya, C., Heuel, M., Terranova, M., Blanckenhorn, W. U., Windisch, W., Kreuzer, M., & Leiber, F. (2022). Genotype-by-Diet Interactions for Larval Performance and Body Composition Traits in the Black Soldier Fly, Hermetia illucens. *Insects*, *13*(5).

Schneider, J. C. (2020). *Effects of light intensity on mating of the black soldier fly (Hermetia illucens , Diptera : Stratiomyidae)*. *6*(2), 111–119.

Shmulevich, Y. (2021). *Anchors in insect projects development (accessed 31.10.2022)*. https://insectprojects.com/blog/f/anchors-in-insect-projects-development

Sindermann, D., Heidhues, J., Kirchner, S., Stadermann, N., & Kuhl, A. (2021). Industrial processing technologies for insect larvae. *Journal of Insects as Food and Feed*, *7*(5), 857–875.

Smetana, S, Spykman, R., & Heinz, V. (2021). Environmental aspects of insect mass production. *Journal of Insects as Food and Feed*, *7*(5).

Smetana, Sergiy, Palanisamy, M., Mathys, A., & Heinz, V. (2016). Sustainability of insect use for feed and food: Life Cycle Assessment perspective. *Journal of Cleaner Production*, *137*, 741–751.

Smetana, Sergiy, Schmitt, E., & Mathys, A. (2019). Sustainable use of Hermetia illucens insect biomass for feed and food: Attributional and consequential life cycle assessment. *Resources, Conservation and Recycling*, *144*, 285–296.

Star, L., Arsiwalla, T., Molist, F., Leushuis, R., Dalim, M., & Paul, A. (2020). Gradual provision of live black soldier fly (Hermetia illucens) larvae to older laying hens: Effect on production performance, egg quality, feather condition and behavior. *Animals*, *10*(2).

Swiss Federal Council. (2012). *Ordinance on Handling Organisms in Contained Systems (814.912) (accessed 31.10.2022)*. http://www.admin.ch/opc/en/classified-compilation/20100803/index.html

Tomberlin, J. K., & Sheppard, D. C. (2002). Factors influencing mating and oviposition of black soldier flies (Diptera: Stratiomyidae) in a colony. *Journal of Entomological Science*, *37*(4), 345–352.

Triunfo, M., Tafi, E., Guarnieri, A., Salvia, R., Scieuzo, C., Hahn, T., Zibek, S., Gagliardini, A., Panariello, L., Coltelli, M. B., De Bonis, A., & Falabella, P. (2022). Characterization of chitin and chitosan derived from Hermetia illucens, a further step in a circular economy process. *Sci Rep*, *12*(1), 6613.

United States Department of Agriculture (USDA). (2022). *USDA market news: National weekly ag energy round-up report, price for yellow grease (accessed 31.10.2022)*. https://www.ams.usda.gov/mnreports/lswagenergy.pdf

Ushakova, N. A., Dontsov, A. E., Sakina, N. L., Ratnikova, I. A., Gavrilova, N. N., Garmash, N. Y., Bastrakov, A. I., & Kozlova, A. A. (2018). Melanin and Melanogenesis at Different Life Stages in Hermetia illucens. *Biology Bulletin*, *45*(1), 47–50.

Üstüner, T., Hasbenli, A., & Rozkosny, R. (2003). The first record of Hermetia illucens (Linnaeus, 1758) (Diptera, Stratiomyidae) from the Near East. *Studia Dipterologica*, *10*(1), 181–185.

Vandeweyer, D., Smet, J., Looveren, N., & Van Campenhout, L. (2021). Biological contaminants in insects as food and feed. *Journal of Insects as Food and Feed*, 1–16.

Veldkamp, T., & Bosch, G. (2015). Insects: a protein-rich feed ingredient in pig and poultry diets. *Animal Frontiers*, *5*(2), 45–50.

Veldkamp, T., Claeys, J., Haenen, O. L. M., van Loon, J. J. A., & Spranghers, T. (2021). *The basics of edible insect rearing. Handbook for the production chain*. Wageningen Academic Publishers.

Veldkamp, T., Van Duinkerken, G., Van Huis, A., Lakemond, C. M. M., Ottevangen, E., Bosch, G., & Van Boekel, M. (2012). *Insects as a sustainable feed ingredient in pig and poultry diets - a feasibility study*. Wageningen UR Livestock Research.

VWR. (2022). *Melanin price per gram from MP Biomedicals (accessed: 31.10.2022)*. https://us.vwr.com/store/product/14513203/melanin

Wang, Y.-S., & Shelomi, M. (2017). Review of Black Soldier Fly (Hermetia illucens) as Animal Feed and Human Food. *Foods*, *6*(10), 91.

Yen, A. L. (2015). Insects as food and feed in the Asia Pacific region: Current perspectives and future directions. *Journal of Insects as Food and Feed*, *1*(1), 33–55.

Zhang, J., Huang, L., He, J., Tomberlin, J. K., Li, J., Lei, C., Sun, M., Liu, Z., & Yu, Z. (2010). An artificial light source influences mating and oviposition of black soldier flies, Hermetia illucens. *Journal of Insect Science*, *10*(1), 1–7.

Appendix A: List of BSF companies worldwide

Name	Region	Website
153FARM	Indonesia	
Agrilife	Tanzania	https://agrilife.co.tz/
Agroloop	Hungary	http://www.agroloop.eu/
Agronutris	France	https://www.agronutris.com/
Alpha Chitin	France	http://alpha-chitin.com/
Alpha Protein	Germany	https://www.alpha-protein.de/
Bardee	Australia	https://www.bardee.com/
Beta Bugs	UK	http://betabugs.uk
BioBuu	Tanzania	https://www.biobuutz.com/
Bioconversion SA	Ecuador	
Biocycle	Indonesia	https://biocycleindo.com/
Biofly	Colombia	https://www.biofly.co/
Bioflytech	Spain	https://bioflytech.com/
Biovert Protein	Thailand	https://www.biovert-protein.com/
Blueprotein	Morocco	https://blueprotein.ma/
Blueprotein	Thailand	https://blue-protein.com/
Briquette du Kivu	Democratic Republic of the Congo	
BSF Breeding	South Africa	https://bsfbreeding.com/
Bug's Life	Kenya	https://www.bugs-life.com/
Buzzfly	Brazil	https://buzzfly.com.br/
Chanzi	Tanzania	https://www.chanzi.co/
Cycle Farms	France	https://www.cyclefarms.com/
Ecodudu	Kenya	https://ecodudu.com/
Ecofly	Austria	https://www.ecofly.at/
Ecofly Waste Solutions	Malaysia	https://ecoflymalaysia.weebly.com/
Ekobelok	Russia	https://hermetia.ru/
Enorm Biofactory	Denmark	https://enormbiofactory.com/
Enterra Feed Corporation	Canada	https://enterra.com/
Ento Industries	Singapore	https://www.entoindustries.com/
Entobel	Vietnam	https://www.entobel.com/
Entocycle	UK	https://www.entocycle.com/
Entofarm	Zambia	https://entomofarm.biz/
Entofarms	Ghana	
Entofood	Malaysia	www.entofood.com

Entogreen	Portugal	https://www.entogreen.com/
Entomo Agroindusrtial	Spain	https://entomoagroindustrial.com/en/
Entomonutris	Morocco	https://entomonutris.com/
Entoprotech	Israel	https://entoprotech.com/
Entosystem	Canada	https://entosystem.com/
Enviroflight	USA	www.enviroflight.net
F4F	Chile	https://f4f.cl
Farmcycle	Germany	https://www.farmcycle.de/
Farminsect	Germany	https://farminsect.eu/en/
Feedect	Spain	https://feedect.com/
FiveDOL Upcycling corp.	Philippines	https://limadol.com/
Flyfarm	Singapore	https://flyfarm.com/
Flyfarm	Australia	https://flyfarm.com.au/
Flylab	Thailand	www.flylabfeed.com
Freeze M	Israel	www.freeze-em.com
Future Green Solutions	Australia	https://www.futuregreensolutions.com.au/
GoTerra	Australia	https://goterra.com.au/
Hermetia	Germany	www.hermetia.de
Hermetia Bio Science	Indonesia	http://hermetiabioscienceeurope.com/
Hexabiotech	Mexico	https://hexabiotech.com/
Hexafly	Ireland	https://hexafly.com/
Hipromine	Poland	https://hipromine.com/
Illucens	Germany	https://www.illucens.com/
Innovafeed	France	https://innovafeed.com/
Innovafeed	USA	https://innovafeed.com/
Inprotin	Guatemala	https://www.inprotin.com/
Inseact	Singapore	https://inseact.com/
Inseco	South Africa	https://inseco.co.za/
Insect Feed Technologies	Singapore	
Insect Revolution	Chile	
Insectifii	India	https://insectifii.com/
InsectiPro	Kenya	https://www.insectipro.com/
Insects4Feed	Nigeria	https://insects4feed.org/
Insectta	Singapore	https://www.insectta.com/
Insectum	Lithuania	www.insectum.eu
Insectum	Denmark	https://insectum.farm/
Inspro	UK	https://www.inspro-uk.com/
Invertapro	Norway	www.invertapro.com
Kanyazulu Farm	Malawi	
Life Origin	Malaysia	https://lifeorigin.my/

Little Fat Worm Biotechnology Company Ltd.	China	www.littlefatworm.com
Loopento	Iran	
Made by Made	Germany	https://madebymade.eu/
Magalarva	Indonesia	https://magalarva.com/
Mago Farm	Rwanda	https://magofarm.co.rw/
Magprotein	Nigeria	www.magprotein.ng
Maltento	South Africa	https://www.maltento.com/
Marula Proteen Limited	Uganda	https://weareproteen.com/
Meruoca	Brazil	https://www.meruoca.bio/
Mobius Farms	Australia	https://www.mobiusfarms.com/
Mutatec	France	https://mutatec.com/
Nambu	South Africa	https://www.nambugroup.co.za/
Nasekomo	Bulgaria	www.nasekomo.life
Nextalim	France	www.nextalim.com
Nextprotein	France	http://nextprotein.co/
Nextprotein	Tunisia	http://nextprotein.co/
NutriEnto	Kenya	http://nutriento.co.ke/
NutriFly	Liechtenstein	www.nutrifly.li
Nutrisek	South Africa	
Nutrition Technologies	Malaysia	https://www.nutrition-technologies.com/
Oberland Agriscience	Canada	https://www.oberlandagriscience.ca/
Prezero	USA	https://prezero.us/organics-recycling
Probenda	Germany	https://probenda.de/
Procens	Argentina	procens.org
ProNuovo	Costa Rica	https://pronuvo.com/
Proteina	Thailand	https://proteina-ltd.com/
Protenga	Malaysia	www.protenga.com
Protifly	France	https://protifly.com/
Protix	Netherlands	https://protix.eu/
RavenFeed	Netherlands	https://ravenfeed.nl/
Ressect	Kenya	https://ressect.com/
River Road Research	USA	www.riverroadresearch.com
Sanergy	Kenya	www.saner.gy
Sfly Comgraf SAS	France	http://sflyproteins.com/
Siam Bio Insect	Thailand	
Symton BSF	USA	https://symtonbsf.com/
The Bug Picture	Rwanda	https://www.thebugpicture.com/
The Bug Picture	Kenya	https://www.thebugpicture.com/

The Insectary	Kenya	https://theinsectary.co.ke/
TiciInsect	Switzerland	http://ticinsect.ch/
Unique	China	www.gzunique.com.cn
Unique Biotech	Malaysia	https://uniquebiotech.com.my/
Vivotein	USA	https://www.vivotein.com/
West African Feeds	Ghana	www.westafricanfeeds.com
8circular	Spain	https://8circular.eu/

Appendix B: Key company profiles

Business model: Animal feed production

Agronutris		
Headquarters: Toulouse, France	*Founded*: 2011	Agronutris
C-level: Cedric Auriol, Mehdi Berrada	*Contact*: contact@agronutris.com	
Website: https://www.agronutris.com/	*Investment*: EUR 100 million (2021)	
Feedstock: Agro-industry byproducts	*Products and market*: Protein meal, fats, frass. Focus on pet food and aquaculture	
Agronutris focused on rearing the mealworm in their first years. They then decided to switch to BSF due to its shorter life cycle, bioconversion efficiency, and feedstock plasticity. Their first industrial-scale facility under construction in Rethel, France is expected to start production in 2023 (5,000 tons protein meal/year). Bühler AG is the EPC and main technology provider. A second large-scale facility in France is in planning.		

Enterra		
Headquarters: Maple Ridge, British Columbia, Canada	*Founded*: 2007	Enterra™
C-level: Dave Lemmon	*Contact*: info@enterrafeed.com	
Website: https://enterra.com/	*Investment*: USD 10 million (2014), USD 6 million (2021)	
Feedstock: Pre-consumer recycled food products	*Products and market*: Whole dried larvae, protein meal, fats, frass. Focus on backyard poultry, wild bird, pet food, and aquaculture	
Enterra pioneered the approval of insects in animal feed in North America. It was the first company to receive approval from the Canadian Food Inspection Agency (CFIA) for use of dried larvae in feed for salmonids (salmon, trout, arctic char), tilapia, and poultry. Enterra also led the first approvals in the US, with the Association of American Feed Control Officials (AAFCO) adding dried BSF larvae to its ingredient list for salmonids. Enterra runs a BSF facility in excess of 100 tons/day producing 10 tons/day of BSF larvae.		

Entobel		
Headquarters: HQ Singapore, operation in Vietnam	*Founded*: 2013	Entobel
C-level: Gaëtan Crielaard, Alexandre de Caters	*Contact*: info@entobel.com	
Website: www.entobel.com	*Investment*: USD 3.3 million (until 2021), USD 30 million (2022)	
Feedstock: EU standards, no animal-derived ingredients	*Products and market*: Protein meal, fat, frass	
Since 2019, Entobel operates a BSF facility in the southern Dong Nai province of Vietnam with a capacity of 1,000 tons of insect meal per year. Since 2013, Entobel has been running a commercial-scale production site in Vietnam and exporting products worldwide. The company plans to set up a second plant by 2023. It recently closed a USD 30 million funding round to meet these ambitions.		

Enviroflight		
Headquarters: Apex, North Carolina, US	*Founded*: 2009	
C-level: Liz Koutsos	*Contact*: info@enviroflight.com	
Website: https://www.enviroflight.net/	*Investment*: USD 20 million (2020)	
Feedstock: Pre-consumer agri-food byproducts	*Products and market*: Dried larvae, protein meal, fats and frass for poultry, aquaculture, pets, exotic and young animals, and fertilizer markets	
Originally based in Ohio, the headquarters have moved to Kentucky and recently to North Carolina. Since 2018, Enviroflight has been operating the largest BSF facility in the US in Maysville, Kentucky (soon to be replaced by InnovaFeed). In 2020, Darling Ingredients, a global developer and producer of sustainable natural ingredients, acquired Enviroflight (after owning 50% since 2016).		

Hipromine		
Headquarters: Robakowo, Poland	*Founded*: 2015	
C-level: Damian Józefiak	*Contact*: info@hipromine.com	
Website: www.hipromine.com	*Investment*: PLN 26.1 million (EUR 5.7 million) (2021)	
Feedstock: Plant-based recycled food	*Products and market*: Insect meal, live insects, fats, frass, especially for pet food	
Hipromine is operating its first BSF facility in Poland. It recently raised in the excess of 5 million euros to build one more facility. In 2022, it purchased 42,000 m^2 of land for the second production facility. With this facility, the company aims to produce at the level of 50,000 tons of insect-based products annually by 2023.		

Innovafeed		
Headquarters: Paris, France	*Founded*: 2015	
C-*level:* Clement Ray, Aude Guo, Bastien Oggeri	*Contact*: contact@innovafeed.com	
Website: https://innovafeed.com/	*Investment*: EUR 55 million (2018), EUR 140 million (2020), EUR 250 million (2022)	

Feedstock: Pre-consumer, traceable agricultural byproducts	*Products and market:* Protein meal, fats, frass. Focus on aquaculture (salmon and shrimp) and pet food. Fat for poultry and pig feeds
InnovaFeed has been operating a pilot-scale facility in Gouzeaucourt, France, since 2017. Since 2019, InnovaFeed has had a partnership with Cargill, a large, global, US-based food corporation. In 2020, they started operation of their first full-scale facility with a capacity of 70,000 tons of feedstock/year producing 15,000 tons of protein meal, 5,000 tons of fat, and 50,000 tons of frass, co-located with the Tereos starch and Kogeban biomass plant. A similar-sized facility is under construction in Decatur, Illinois, US, based on corn byproducts under a collaboration with ADM (Archer-Daniels-Midland) and a US multinational food processing and commodities trading corporation. This facility is benefiting from 28 MW of residual energy that was previously unused by the ADM process.	

NextProtein		
Headquarters: HQ Paris, France, operation in Tunisia	*Founded*: 2015	nextProtein feeding the future
C-level: Syrine Chaalala, Mohamed Gastli	*Contact*: m.gastli@nextprotein.co	
Website: http://nextprotein.co/	*Investment*: EUR 1.3 million (2017), EUR 10.2 million (2020)	
Feedstock: Plant-based agri-food byproducts (no wastes)	*Products and market*: Protein meal, fats, frass	
Nextprotein manufactures BSF-based products in the Cap Bon region in Tunisia. Its HQ, R&D, and sales are in France. NextProtein claims to have a lower cost manufacturing model than most of its competitors, especially on the energy side. The company has approval to sell its product in the EU and is GMP+ certified. In the next years, second and third plants are planned for Asia and South America. Current capacity in 2022: 400 MT of insect meal annually. 2500 MT projected in 2023.		

Nutrition Technologies		
Headquarters: HQ Singapore, operation in Malaysia and Vietnam:	*Founded*: 2014	
C-level: Tom Berry, Nick Piggott	*Contact*: info@nutrition-technologies.com	
Website: https://www.nutrition-technologies.com/	*Investment*: USD 14 million until 2021	
Feedstock: Pre-consumer agri-food byproducts such as palm oil mill decanter byproduct	*Products and market*: Protein meal, fats, frass. Focus on aquaculture with smaller amounts into poultry and pet food	
Nutrition Technologies is operating one of the largest BSF facilities in Southeast Asia, commissioned at the end of 2020. It has a capacity of 12,000 tons of frass, 3,000 tons of protein meal, and 1,000 tons of fat and is based in Iskandar Puteri, Johor, Malaysia. Multi-day feedstock fermentation with beneficial bacteria is an important part of their facility. Nutrition Technologies has aspirations to expand into other Southeast Asian markets in the coming year(s), including Thailand and Indonesia.		

Protenga		
Headquarters: HQ Singapore, operation in Malaysia	*Founded*: 2016	
C-level: Leo Wein	*Contact*: leo.wein@protenga.com	
Website: www.protenga.com	*Investment*: USD 2 million (2020)	
Feedstock: Homogenous pre-consumer agri-food byproducts (e.g., okara, spent grain)	*Products and market*: Protein meal, fats, and frass. Focus on pet food	
Protenga has been headquartered in Singapore since 2016 and has operated a pilot-scale factory in Malaysia since 2021. In 2022, they launched their own pet food brand Yum Grubs (https://yumgrubs.com). In collaboration with Roslin Technologies (who is also an investor), Protenga also aims to identify more efficient BSF strains. Protenga also works toward providing turnkey BSF facilities via their proprietary "Smart Insect Farm" system similar to the grow-out model common in the poultry industry with a capacity in the order of 20-60 tons of feedstock/day.		

Protix		
Headquarters: Dongen, NL	*Founded*: 2009	
C-level: Kees Aarts	*Contact*:	
Website: https://protix.eu/	*Investment*: EUR 45 million (2017), EUR 15.5 million (2021), EUR 50 million (2022)	

Feedstock: Pre-consumer agri-food byproducts	*Products and market*: Protein meal, fats, frass, larval pulp. Focus on pet food market, but also aquaculture, livestock, and human food.

Protix is operating the first large-scale and automated BSF facility based in Bergen op Zoom, the Netherlands. The 15,000 m^2 facility was established in 2019 as part of a joint venture with Bühler started in 2017, the main technology provider. This joint venture was terminated in 2020. The facility is still operational and Protix claims to have recently improved production by ±20% with a multi-year selective breeding program. Over the years, Protix has worked to create clients for its customers such as the Oerei (an egg from hens partially fed with live BSF larvae), sustainable pet food (with Purina, a Nestle brand), and the friendly fish label. In early 2022, Protix raised 50 million EUR to expand in North America and Europe.

Business model: Waste management

AgriProtein		
Headquarter: London, UK	*Founded*: 2008	
C-level: Jason Drew	*Contact*:	
Website: https://agriprotein.com (offline)	*Investment*: USD 11 million initial investment + 2 Gates grants, USD 105 million (2017)	
Feedstock: (Packages) food waste	*Products and market*: Protein meal, lipids, and frass	
Agriprotein was the pioneering company in the BSF larvae industry. They built the first large BSF facility in Cape Town, South Africa in 2015. From 2017, under a partnership with the Austrian Engineering company Christof Industries, AgriProtein planned to roll out factories globally. It had planned to develop 20 fly farms in North America, as part of a larger goal of building 100 fly farms by 2024 and 200 by 2027. They also bought Milibeter, a Belgian company, in 2017 and established a project in California and a research center in Singapore. Agriprotein entered administration in 2021.		

BioflyTech		
Headquarters: Murcia, Spain	*Founded*: 2012	
C-level: Jesús Rodriguez	*Contact*:	
Website: https://bioflytech.com/	*Investment*: EUR 18 million (2021)	
Feedstock: Organic byproducts	*Products and market*: Protein meal, fat, frass. Focus on pet food and aquaculture	
BioflyTech, driven by Alicante entomologist Santos Rojo and backed by the investment fund Moira Capital, is building a new plant (20,000 m^2) near Murcia.		

Hexafly		
Headquarters: Meath, Ireland	*Founded*: 2016	
C-level: Alvan Hunt	*Contact*:	
Website: https://hexafly.site.xyz/	*Investment*: EUR 2.2 million (seed), EUR 3 million (Series A)	
Feedstock: Food waste	*Products and market*: Live larvae, oil, insect meal, frass	
Vertical BSF farm in Ireland which has raised 5.2 million EUR so far. Series B funding in 2021/22 with plans to open a plant producing 10,000 tons of insect protein each year in 2024.		

Sanergy		
Headquarters: Nairobi, Kenya	*Founded*: 2009	
C-level: David Auerbach	*Contact*:	
Website: www.saner.gy	*Investment*: USD 1.5 million (2013), USD 1.7 million (2016), USD 2.5 million (2021), USD 19 million (2022)	
Feedstock: Human feces, fruit and vegetable waste, animal manure	*Products and market*: Dried larvae and compost	
Sanergy provides solutions to sanitation in urban slums. They provide container-based sanitation on a franchise model, including a collection service and treatment by BSF larvae together with other urban biowastes. Sanergy established its pilot facility in 2011. In 2020, Sanergy opened a treatment facility with a capacity to treat 200 tons of biowaste/day. Sanergy has plans to roll out its plants across Africa and into South America and Asia.		

PreZero		
Headquarters: Mira Loma, USA, BSF facility in Jurupa Valley, USA	*Founded*: 2009	
C-level:	*Contact*: ian.banks@prezero.us	
Website: https://prezero.us/organics-recycling/black-soldier-fly-technology	*Investment*: USD 11 million initial investment + 2 Gates grants, USD 105 million (2017)	
Feedstock: (Packaged) food waste	*Products and market*: Animal feed ingredients	
PreZero is a global waste management company belonging to the Schwarz Group. Organic waste management within PreZero was first conducted as the joint venture of Bioko with AgriProtein in 2020, which was continued by PreZero following the insolvency of AgriProtein in 2021. PreZero runs a test facility in the vicinity of Los Angeles, California with a capacity to treat 1 ton of biowaste per day. An industrial-scale operation is under construction.		

Food for the Future		
Headquarters: Talca, Chile	*Founded*: 2014	
C-level: Cristian Emhart	*Contact*: cristian@f4f.cl	
Website: https://f4f.cl	*Investment*: USD 4.5 million (2021)	
Feedstock: Agroindustrial waste	*Products and market*: Pet food, dried larvae, aquaculture feed (in future defatted meal, oil, frass)	
Food for the Future operates its plant in Talca, Chile. In the first years, F4F relied mostly on investments by a small group of friends to founder and CEO Cristian Emhart. In 2021, they were able to raise USD 3-4 million to increase the capacity of the plant from 10-20 tons of insect meal per month to 150 tons per month over the next two to three years. F4F has expansion plans in the USA, Colombia, Ecuador, and Peru, as well as in some European countries. Since 2022, there has been a collaboration with Truchas Insect Fed to feed salmon with insect protein on a large scale.		

Business model: Young larval offspring

Guangzhou Uniqe Biotechnology		
Headquarters: Guangzhou, China	*Founded*: 2014	
C-level: not available	*Contact*: gzunique@guangzhouunique.com	
Website: https://en.gzunique.cn/	*Investment*: not available	
Unique sells larval products but was the first company selling large amounts of BSF eggs (e.g., hundreds of grams to kgs). With their own R&D center, they are holding a number of national and international patents. They have operations in a number of cities such as Guangzhou, Haikou, Chengdu, and Huizhou.		

BSF Breeding		
Headquarters: Cape Town, SA	*Founded*: 2020	
C-level: Olaf Jebens	*Contact*: olaf@bsfbreeding.com	
Website: https://bsfbreeding.com/	*Investment*: not available	
BSF Breeding is located in South Africa and focuses on the BSF breeding cycle. BSF Breeding ships neonates all over the world at USD 2.40/g (+shipping) (at the time of writing). Assuming a survival of 100%, this adds costs of >USD 0.15 per kg of fresh larvae produced.		

FreezeM		
Headquarters: Nachshonim, Israel	*Founded*: 2018	
C-level: Idan Alyagor	*Contact*: idan@freeze-em.com	
Website: www.freeze-em.com	*Investment*: not available	
FreezeM offers shipping of neonates. Additionally, with their large in-house R&D capacities, FreezeM developed a preservation technology to pause the larval development for up to 14 days. This technology allows facilities to handle seed stock more flexibly and it buffers shipping delays. They currently price their product according to the number of neonates shipped. However, as the market evolves, they would be interested in offering a "larvae as a service" model where the client pays a fixed price matching its production capacity. This		

model still requires some development on the business side but eventually it will lead to another risk reduction in the supply chain.

Business model: High-value products

Alpha Chitin	
Headquarters: Lacq, France	*Founded*: 2016
C-level: Jerome Delay	*Contact*: contact form on website
Website: http://alpha-chitin.com/	*Investment*: not available
According to Alpha Chitin, they developed methods and tools to grow BSF larvae allowing an unprecedented control over biological development (reproduction, development, biosafety, dedicated environment) using a specific diet that meets all EU standards, is non-GMO certified, and can be fully organic. Chitin and chitosan are extracted from BSF larvae, but also from krill and fungi. Chitin/chitosan finds its application in the biomedical/pharmaceutical sector as well as in cosmetics, agrifood, agriculture, and environmental management (drinking water treatment, bioremediation, sludge dewatering).	

insectta	
Headquarters: Singapore	*Founded*: 2018
C-level: Chua Kai-Ning	*Contact*: hello@insectta.com
Website: https://www.insectta.com/	*Investment*: not available
Besides regular products such as dried larvae, frass, or BSF eggs, insectta produces high-value products such as chitosan, organic semiconductors, and probiotics from larvae. The company broke even in 2020. Additionally, they offer farm tours and workshops for school children to learn about circular economy and the BSF.	

About the Subnational Climate Fund:

The Subnational Climate Fund (SCF) is a global blended finance initiative that aims to invest in and scale mid-sized (5 – 75 M $USD) subnational infrastructure projects in the fields of sustainable energy, waste and sanitation, regenerative agriculture and nature-based solutions in developing countries.

The SCF finances projects with a blend of concessional and conventional capital, along with Technical Assistance grants that help mitigate risk and ensure financial and environmental goals are achieved.

For further information about the SCF, visit: www.subnational.finance