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Article *in* Entomologia Generalis · February 2024

DOI: 10.1127/entomologia/2023/2279

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Entomologia Generalis
Published online February 2024

A worldwide overview of the status and prospects of edible insect production

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With 1 figure and 4 tables

Abstract: There has been continuous and growing interest in edible insects. Worldwide, various levels of insect farming are emerging, ranging from small domestic farms to vertical farms reaching heights of 36 meters, accommodating several million growing insects. The appeal of insects lies in their ecological benefits, as they contribute to the valorization of underutilized organic residues while requiring minimal space and water. The selection of insect species is influenced not only by their biology and behavior but also by local preferences and customs, varying with the scale of production and geographical location. This review article aims to provide an updated overview of the main insect species produced across different continents, their current level of industrialization, and production prospects based on available literature.

Keywords: entomophagy; insect food; insect industry; insect farming; insect marketing

DOI: 10.1127/entomologia/2023/2279
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1 Introduction

Edible insects are an essential part of many nations' and ethnic groups' diets (van Huis 2013). It is estimated that insects are part of the traditional meals of at least two billion people who share about 1600 identified species (Van Itterbeeck & Pelozuelo 2022). In most of the cases the knowledge associated with the use of insect resource as food and medicine largely remains undocumented and is usually transmitted generation after generation verbally (Ghosh et al. 2020). Most of the insects consumed in the world are collected seasonally from the wild and are processed (sun drying, smoking and/or roasting), packaged, and stored for household consumption or sold on markets (Caparros Megido et al. 2016). Wild collection can pose detrimental effects on both human and animal health, as well as the environment (Ramos-Elorduy 2006). Many of the species collected are phytophagous, and they have the potential to bioaccumulate toxic or anti-nutritional substances from plant materials, along with compounds present in their environment, such as heavy metals or pesticides. Furthermore, there is a risk that insect collection could evolve into a threatening activity for the species or its environment, especially in cases of overexploitation (van Huis 2019; Yen 2009). Promoting sustainable production techniques for species is considered a viable approach to mitigating sanitary risks for consumers. Simultaneously, the development of "Edible Insects Exploitation and Trading Norms and Legislation," along with the establishment of reserve zones, can contribute significantly to preventing the extinction of these species and safeguarding their respective environments (Caparros Megido et al. 2015; Gahukar 2016; Ramos-Elorduy 2006). Farmed insects typically feed on a wide range of inexpensive forages or organic side streams (Caparros Megido et al. 2016; van Broekhoven et al. 2015). Remarkably, some edible insect species have showcased feed conversion efficiencies ranging from 50–70%, surpassing those of chicken (38–43%) and cattle (10–12%). Notably, insect production demands less land and water, and exhibits lower greenhouse gas emissions compared to traditional livestock (Oonincx et al. 2015).

The most straightforward production system involves the semi-cultivation or semi-domestication of insects. This method entails maintaining the insects in their natural environment while modifying it to enhance productivity. The objective is to better align the environment with the insect's biology and ecology (Van Itterbeeck & van Huis 2012). With this approach insects are naturally available for the locals, habitat conservation is facilitated and food security is enhanced (Gahukar 2016). In sub-Saharan Africa, local people buy young caterpillars (*Imbrasia obscura* Butler or *Cirina forda* Westwood) on the market and place them on the trees around houses. When the larvae matures, people have only to leave their homes and harvest them easily (Van Itterbeeck & van Huis 2012). Domestication, on the other hand, refers to the process of breeding and rearing in complete captivity. One of the most well-known examples of domesticated insects is the silkworm (*Bombyx mori* (L.)), which has been domesticated in China and India for thousands of years for the silk production. The selection of insects for domestication should be guided by various criteria, including size, social behavior (with an emphasis on minimizing cannibalism), safety for handlers, resistance to diseases, reproductive potential, survival capabilities, nutritional value, and the feasibility of storage and commercialization (Schabel 2010). Generally, it is expected that the target insect produces many eggs with a high viability rate, that it grows rapidly with maximum synchronization pupation to facilitate harvesting of individuals and that it has a high conversion rate of by-products (Caparros Megido et al. 2015). In recent years, several species of insects have already been domesticated, including mealworms (*Tenebrio molitor* (L.)) or lesser mealworm (*Alphitobius diaperinus* (L.)) and crickets (*Acheta domesticus* (L.) for human consumption and black soldier fly or BSF (*Hermetia illucens* (L.)) for animals.

Most insect farms worldwide firstly consist of pet feed, fish food, pest control companies (particularly for biocontrol), research laboratories, and aquaculture companies. In the United States and Europe, an increasing number of companies are now growing edible insect species for human food and animal feed and, in Asia, bigger farms produce insects for human food, animal feed and medicinal applications (Dossey et al. 2016). While there is no clear distinction between small vs large-scale production of insect as feed and food, it is supplied on small, medium, and large scales (van Huis 2020). Small-scale livestock production describes a type of production system in which the farm unit (e.g., a single farmer, a couple, or a cooperative) represents the owner(s), worker(s), and decision-maker(s) of the farm (Halloran et al. 2018). Small-scale livestock production is recognized for its effectiveness in improving the livelihoods and quality of life of rural households by improving the equitable distribution of income, boosting the local market, and ensuring the conservation of local species and related agricultural practices. It is more difficult to differentiate between medium and large scale although, according to Dicke (2019), small-scale initiatives would produce 10–50 kg of fresh insect biomass weekly; medium-scale initiatives would produce 0.4–21 tons weekly; and large-scale initiatives would process more than 10 tons of organic waste weekly and/or export insects or their derivatives (Caparros Megido et al. 2017).

As this is a very new industry, particularly for North America and Europe, scale is relatively small, efficiency is suboptimal, many processes are still done manually (i.e. egg collecting, or handling of crates) inducing high costs of production although large companies are emerging (Dossey et al. 2016). The insect farming industry continues to grow and is expected to become more profitable (Verner et al. 2021). It is estimated that the edible insect market will be worth approximately 8 billion USD by 2030 (Verner et al. 2021). These companies conduct in-house research and development and restrict access to their technological advances through the production of patents. To insure a bright future for the industry, a rapid and efficient growth is critical and the costs of farmed insects need to be reduced to at least 25% to be competitive with other animal based protein commodities (Dossey et al. 2016). Depending on the regions of the world, the development of edible insect production has followed very specific paths in relation to the introduction of this new food source, in particular related to the production process but also to legislation and acceptance by the consumer (Bosch et al. 2019; Grabowski et al. 2020; Petrescu-Mag et al. 2022).

The decision to conduct a review on the worldwide status and prospects of edible insect production stemmed from the growing significance of edible insects as a potential sustainable food source. Our goal was to comprehensively assess the current state of edible insect production globally, examining the existing practices, challenges, and opportunities. Given the increasing interest in alternative protein sources, we believed that a thorough review of edible insect production would contribute valuable insights to researchers, policymakers, and industry stakeholders. Through the synthesis of current knowledge, identification of existing gaps, and exploration of future prospects, our objective was to create a comprehensive resource that fosters a more profound comprehension of the edible insect industry and guides future research and development in this field.

2 Africa

Entomophagy is a widespread practice in Africa where insects are consumed as part of traditional diets (van Huis 2013). More than 470 species of edible insects belonging to the orders Blattodea, Coleoptera, Diptera, Hymenoptera, Isoptera, Lepidoptera, Odonata, and Orthoptera occur in Africa (Kelemu et al. 2015). These insects are mainly collected from the wild, thus their use as a food source is limited by their seasonal availability. There are approximately 2300 active insects' farms across the continent, the majority of which are small scale insect farms for about 18 edible insect species identified as suitable for farming (Tanga et al. 2021). The majority of these farms were established after 2010, following an awareness campaign on insects domestication for food and feed launched by FAO in 2013 (van Huis et al. 2013).

2.1 Black soldier fly

BSF has gained worldwide recognition as an alternative protein source in the animal feed production industry (Bulinda et al. 2023). BSF stands as the primary arthropod species excelling in the conversion of organic waste into high-quality, nutrient-rich biomass. Positioned as the crown jewel within the insect feed production industry, BSF has the potential to significantly impact economies in the developing world across various value chains, including aquaculture, swine, poultry, and more. Its contribution extends beyond providing a sustainable ingredient for animal feed, encompassing job creation, poverty reduction, and a positive influence on the national gross domestic product (Abro et al. 2022; Tomberlin & van Huis 2020). Additionally, by efficiently reducing waste and safeguarding the environment, BSF emerges as a multifaceted solution with far-reaching benefits (Tanga et al. 2021).

2.1.1 Farming

The feasibility of trapping and culturing wild colonies of BSF allowed the development of small-holder BSF farming (Ewusie et al. 2019). Medium to large-scale farms have emerged in Eastern Africa and include: InsectiPro LTD., Regen Organics (formerly called Ltd.), Marula Proteen Ltd., Bugslife Protein Ltd., Biobuu Ltd., The Bug Picture Ltd., Protein Kapital Ltd., and the Insectary Ltd. These enterprises specialize in the recycling of organic waste, transforming it into nutrient-rich biomass suitable for inclusion in feed formulations. Some of these operations have implemented automation to streamline processes, effectively lowering production costs (Climate Chance 2023; Tanga et al. 2021). By taking such an approach, BSF farmers are not competing with other industries (e.g., aquaculture, livestock, poultry) to produce insect biomass; in fact, they are able to recycle organic waste streams as previously mentioned. Doing so allows for synergy across agricultural sectors; one industry's waste is another industries feedstock. In West Africa, a BSF breeding system was developed and tested for production of BSF meal as an ingredient in fish feed in Benin (Gougbedji et al. 2021). The technology was found to be suitable for use by small holder farmers and produced BSF with adequate nutrients with the potential of substituting fish meal in formulation of fish feed. Several companies involved in BSF production have been reported as Agrimax, Insects4Feed, Magprotein, Sectagreen and Urban Akwu in Nigeria; and Entofarm, Neat Eco-Feeds and West African Feeds in Ghana but also Agro Solution, Maltento, Inseco and Mangau Animal Feeds in South Africa and Susamati in Mozambique (Footprints Africa 2022).

The rapid expansion of BSF rearing has led to forging of partnerships between donor organization and entrepreneurs. In 2021, the Japan International Cooperation Agency invested US$2.5 million in Regen Organics which owns the largest insect feed industry in East Africa located in Kenya but is preparing to expand their business to other African countries (JICA 2021). In 2022, The Norwegian Agency for Development Cooperation launched a three-year BSF project in Ghana, Mali and Niger to improve urban sanitation and address bio-waste and help small scale fish, chicken and vegetable producers (Insect School 2023).

2.1.2 Rearing systems and substrates

Production of BSF occurs in two major steps carried in a reproduction and production unit which consist of adults and growing larvae respectively (Gougbedji et al. 2021). The process involves three phases: egg production, egg hatching and larval growth and harvesting (Verner et al. 2021). The egg laying phase requires netted cages where adults swarm and mate, and a special substrate for oviposition (Verner et al. 2021). Recent development concerns the use of artificial light to replace daylight; identification of alternative substrates to stimulate oviposition; and structures that enhance egg laying and hatching. Egg laying structures include 4–5 pieces of cardboard that are held together with rubber band, corrugated cardboard wooden nesting box or specially designed traps (Cortes Ortiz et al. 2016; Gougbedji et al. 2021). Given the BSF's tropical origin, optimal performance is achieved in natural light conditions with an intensity of 110 µmol m2s-1, within a temperature range of 27.5–37.5 °C. Ideal conditions also encompass a relative humidity of 50–90%, moisture content between 40–80%, rearing substrate pH of 6–10, and a photoperiod of 12 hours light (L) to 12 hours darkness (D) (Singh & Kumari 2019). Notably, increased oviposition behavior and enhanced larval development are observed at a density of 8,500 adults/m^3 and 2 larvae/g of waste, respectively (Gougbedji et al. 2021). However, it's essential to note that these conditions are population-specific, and individuals rearing the BSF will need to determine the optimal conditions for their specific context.

Larval rearing can occur in an open system that comprise self-harvesting of larvae or a fully managed system where the final larval instar is sieved out feeding substrate (Gougbedji et al. 2021; Verner et al. 2021). In a fully managed system, rearing of larvae can be done in a stacked crates whereas in the open system, containers of organic substrate can be used to attract wild BSF (Verner et al. 2021). BSF production at industrial or commercial scale occurs through self-harvesting system or the preferred tray or pan system (Yang 2017). The production plants are semi or fully automated and can contain up to 1000 tons of organic waste per day but are less automated compared to the west (Verner et al. 2021). In Africa, the established code of practice permits the rearing of BSFL on a diverse range of promising organic waste streams. These include poultry manure, brewer's waste, kitchen waste, market waste (including decaying vegetables and fruits), pig manure, rabbit waste, fish offal, brewers' spent grains, and, to a lesser extent, human waste (JICA 2021).

2.1.3 Processing and marketing

BSF can be sun dried then milled into powder. Because of their high fat content that increases rancidity, meals are defatted by organic solvents, boiling, or pressing. BSFL contains 40–50% protein which is comparable with the protein content of groundnut cake (45–60%) and soy cake (47–49%) (Caparros Megido et al. 2015). Production of BSF by the top nine farms through a circular economy is estimated at 10,000 metric tons or dried protein per annum; which can substitute soybean and fish in animal feeds that can be used to produce up to 4.7 million chicken (Tanga et al. 2021). It is estimated that BSF production in Africa can produce crude protein worth more than US$2.6 billion (Verner et al. 2021).

Use of BSF meal as a substitute for fish meal in fish feed to reduce the production cost has been suggested since 2007 (Gougbedji et al. 2022). BSFL can also be fed directly to other animals such as chicken and pigs to supplement their existing feed or as an alternative protein source (Climate Chance 2023). As an example, an agripreneur in Kenya reported increased growth rate and higher weights in broilers and faster maturity and higher quantity of lean meat in pigs fed directly on BSFL (Aciar 2021).

2.1.4 Soil amendment

Mass production of insects on organic waste produce large quantities of frass that can be used as soil amendment (Poveda 2021). The soil amendment comprise BSF frass and spent substrate which contains phosphorus, nitrogen and potassium (Verner et al. 2021). Amendment of soil with BSF frass increased the performance of crops such as French beans, kale, tomatoes or maize (Anyega et al. 2021; Beesigamukama et al. 2020). The substantial increases in productivity can be primarily attributed to enhanced soil health, increased organic matter, mitigation of soil acidity, and the effective suppression of soil-dwelling pests and pathogens. Currently, the International Centre of Insect Physiology and Ecology (*icipe*) in Kenya has innovatively crafted various market driven BSF frass products, offered in powdered, liquid, or granulated forms. These products have been enriched with chitin to amplify the advantages associated with pest and disease control, thereby enhancing the efficacy of frass fertilizer. BSF production in Africa produces large quantities of high-quality biological soil amendment (approximately US$ 0.3–0.35 per kilogram) worth more than US$19.4 billion (Tanga et al. 2021).

2.1.5 Bio-waste recycling

Rearing of BSF on organic waste promotes waste recycling and can alleviate solid waste management problem that is rampant in Africa (Singh & Kumari 2019). Considering that an individual larva can ingest between 25 and 500 mg of organic waste daily, contingent upon the substrate type, feeding conditions, and larval size, it is projected that BSF production could potentially recycle approximately 0.09 to 41 million tons of organic waste annually (Abro et al. 2022). Extensive projections indicate that BSF has the capacity to efficiently recycle 200 million tons of bio-waste in Africa, simultaneously contributing to environmental preservation by avoiding approximately 86 million tons of carbon dioxide equivalent emissions annually (Verner et al. 2021). However, the seasonality of plant-based residual streams introduces variability in waste quality for BSF production, impacting large-scale production dynamics (Tanga et al. 2021). Consequently, it becomes imperative to subject certain residual waste streams to pretreatment to enhance their suitability for BSF production. Realizing the full capacity of BSF necessitates the implementation of waste segregation at production points, thereby augmenting the availability of suitable residual waste streams.

2.1.6 Challenges

Although BSF production is a rapidly growing industry in Africa, a couple of challenges may impede sustainable insect farming: 1) lack of global standards and regulations (and therefore lack of clarity on safety and legality) to produce BSF larvae which limits the entry of producers into the market; 2) limited technology and infrastructure such as rearing facilities, waste management systems and feed preparation and storage; 3) low market demand and consumer acceptance of BSF as a food source; 4) inadequate high quality feedstock for production of BSL larvae; 5) high start-up cost and low profitability due to lack of competitiveness with alternative feed sources for production of animal feed; 6) high operational costs and limited access to finances; 7) limited access to skills and technical expertise; 8) complicated logistics and difficult access to supplies and suppliers; and 9) limited research and development for BSF production industry (Footprints Africa 2022; Insect School 2023). Solutions, while not known at the time, can be developed. Of course, efforts are already moving forward, such as identifying appropriate feedstocks (Surendra et al. 2016), expanding regulations (Alagappan et al. 2022), and life-cycle analyses to determine pressure points related to reduce costs and increase profitability (Smetana et al. 2019).

BSF colonies can also be damaged by different organisms such as bacteria (e.g., *Campylobacter* Sebald & Véron), fungi (e.g., *Beauveria bassiana* (Bals.-Criv.) Vuill. (1912)), entomopathogenic nematodes (e.g., *Steinernema carpocapsae* (Weiser), pupal parasitoid (*Eniacomorpha hermetiae* Delvare) and phoretic mites (*Macrocheles muscaedomesticae* (Scopoli) (Jensen & Lecocq 2023; Yang 2017). Hence, it is imperative to establish regular monitoring, enhance quality control, and implement preventive measures to mitigate infestations by pests and pathogens (Tanga et al. 2021; Tanga & Kababu 2023). Collaborations with both the public and private sectors play a pivotal role in formulating policies and regulatory frameworks for the production, safety, and commercialization of BSF products on both national and international scales. The involvement of the engineering sector is crucial for devising cost-effective and energy-efficient structures, as well as machinery and equipment for the large-scale production of BSF. Social scientists will play a vital role in establishing functional linkages to facilitate access to logistics and markets for BSF products. Engaging in partnerships with governmental and financial institutions is essential to broaden access to capital and enhance the acceptability of BSF products. Additionally, the digitalization of certain BSF farming operations can significantly reduce operational costs and boost profit margins, thereby attracting private sector investment. Capacity building and cutting-edge research are indispensable to raise awareness, foster innovation, and provide training for skilled personnel essential to propel the BSF industry forward (Tanga et al. 2021; Verner et al. 2021).

2.2 Crickets

Cricket consumption remains a widespread practice in Africa where 26 species are consumed across 25 countries (Magara et al. 2021). Crickets are consumed as wet fried, dried whole forms or ground into powder and incorporated in food products such as bread, cookies, crackers and flour in order to enhance their palatability. Cricket farming serves as a livelihood source for numerous households, with the price of one kilogram of crickets ranging between US$ 10.0 to 40.0 in both whole and powdered forms. This pricing variability can be attributed to factors such as scarcity and accessibility, stemming from the seasonality of cricket availability, low captive production by industries, and the limited geographical distribution of edible species. The sales locations, ranging from village settings (countryside) to towns and cities, further contribute to the pricing dynamics in the cricket market (Halloran et al. 2018; Magara et al. 2021). Despite the high number of edible cricket species in Africa, the most farmed species include *A. domesticus* and *Gryllus bimaculatus* De Geer 1773. The two cricket species mentioned above are extensively cultivated for food and are particularly favored for their rapid maturity, ease of maintenance, high survival rates, substantial nutritional value, and adaptability to diverse rearing diets (Halloran et al. 2018).

2.2.1 Farming

Small scale production of crickets requires limited space (for example a 5 m × 7 m room) with a few rearing buckets. A medium scale production of crickets can occur in a space about 70 square meters, containing 500 crates; producing 63 million eggs and 3,400 kg of crickets yearly (Flying Food 2023; Oniang'o 2020).

Farming of crickets as food is rapidly expanding in East Africa where there are approximately 518 farmers reported in Kenya and Uganda and over 30 tons of cricket powder produced annually by small and medium enterprises (Tanga et al. 2021). Cricket farming was experimental introduced by two universities in the region in 2014: Jaramogi University of Science and technology and Jomo Kenyatta University of Science and Technology (Kinyuru & Ndung'u 2020). The high adoption of cricket farming in the region is influenced by awareness creation, degree of risk averseness and high sales. A kilogram of whole or dried crickets or cricket powder ranges between US$ 10.9–18.2 (Tanga et al. 2021). In 2016, a group of farmers in western Kenya initiated cricket farming following a one-month training and provision of cricket starter kit (Oniang'o 2020).

The “Flying Food partnership” aims to elevate crickets into a mainstream food product in ten African countries by fostering the development of cricket rearing, processing, and consumption. This initiative resulted in the formation of 120 smallholder cricket farmers, the establishment of two medium-scale companies capable of delivering 50 tons of crickets annually, and the inception of three processing companies involved in the drying, grinding, and packaging of crickets in both Kenya and Uganda. In Nigeria, the project collaborated with a bread and muffins cooperative (Springboard) and received support from USAID. The initiative successfully trained 43 farmers, with 25 of them subsequently establishing their own cricket farms. (Flying Food 2023). Flying Food hopes to kick off crickets’ food business in Malawi, Burundi, and Rwanda.

In 2019, one of the large BSF farms in Kenya, InsectiPro diversified into cricket farming (Flying Food 2023). The farm employs an automated production system that yields more than 30 tons of crickets annually (Tanga et al. 2021). Another well-established cricket farm in Kenya is Mixa. This farm engages in the comprehensive process of rearing, processing, and marketing crickets. Additionally, Mixa plays a crucial role in training smallholder farmers in cricket farming practices and provides them with cricket eggs (Flying Food 2023). Cricket production also occurs in Southern Africa. In 2017, Endoki cricket farming business was reported in South Africa. As a marketing strategy, the farm highlighted the environmental benefits of eating insects to persuade South Africans to include crickets in their daily diets (Scheier 2017). EnseKta, a cricket farm engaged in farming, packaging, and marketing, was established two years later. Specializing in the production of cricket powder, the farm offers a versatile product that can be sprinkled into various food preparations, including salads and smoothies, along with other processed products (de Wet 2021). There is evidence of very small cricket farming in Zimbabwe and also in Madagascar (Verner et al. 2021).

2.2.2 Rearing systems and substrates

Crickets are reared in large buckets, large wash basins covered with blankets, plastic crates and portable pens hermetically sealed but well ventilated (Flying Food 2023; Oniang’o 2020). Rearing containers are fitted with egg trays to provide a hide out for crickets; and fitted with netted material to deter predators and prevent the crickets from escaping (Oniang’o 2020). Large-scale cricket production is conducted in robust concrete pen systems, renowned for their durability and ease of cleaning. Like other rearing containers, these pens are equipped with egg trays serving as the living quarters for crickets. Additionally, they are covered with netted material to deter potential predators (Orinda 2018). Oviposition substrates and diet are provided with the rearing containers or pens. Automated production of crickets has also been reported in Africa where large-scale productions occurs in farms such as Insectipro.

Crickets rearing farms feed crickets on conventional livestock feed that are very similar in composition to poultry feed (Kuo & Fisher 2022). Crickets are also reared on weeds, industrial wasted, food wastes and agro-byproducts (Kuo & Fisher 2022).

2.2.3 Processing and marketing

Crickets can be consumed whole or processed into powder and incorporated into different products such as bread, muffins, biscuits, samosas or fried rice (Kuo & Fisher 2022). Whole crickets are processed through boiling then frying for home consumption or can be frozen (Oniang’o 2020). Crickets can be roasted, sun dried, oven dried, freeze dried or placed in a food dehydrator prior to crushing into powder, then mixed with ingredient of choice that can be used for production of processed products (Verner et al. 2021). Cricket flour can also be defatted to improve its quality. In 2022, InsectiPro launched the brands Chirrups that are fried crickets as snacks that come in different flavors. On in other hand, Mixa farm uses cricket powder to produce bakery products for local market.

Although crickets are mainly produced for food in the region, evidence suggest that cricket producers in Kenya are reported to sell crickets to fish breeders and poultry farmers (Verner et al. 2021). Incorporating crickets into animal feed has the potential to substantially reduce the cost of animal production, particularly when they are produced using weeds and waste side streams (van Huis 2013). Despite their potential use as food, the cricket value chain in Africa faces significant underdevelopment, primarily attributed to elevated production costs, a lack of technical expertise, absence of readily available markets, and a deficit in cricket production expertise (Tanga et al. 2021; Verner et al. 2021). Furthermore, crickets are susceptible to viral, fungal, and bacterial infections, as well as mite infestations, which can result in the collapse of cricket colonies. These challenges have prompted temporary closures of cricket farms by producers in Kenya and Uganda (Flying Food 2023; Tanga et al. 2021).

2.3 Grasshoppers

There are more than 107 species of edible grasshoppers consumed across Africa (Melgar-Lalanne et al. 2019). The most frequently consumed grasshopper species in Africa include *Ruspolia differens* and *Schistocerca gregaria* whose availability is limited by swarming patterns (Tanga et al. 2021). Edible grasshoppers are primarily harvested from the wild, relying on their seasonal availability. Nonetheless, the successful rearing of grasshopper species under laboratory conditions and the emergence of small-scale production units in Europe provide compelling evidence that domestication of these insects is indeed feasible (Paul et al. 2016). Despite the high acceptability of grasshoppers as food and their potentially lucrative selling prices, the profitability of their rearing is hindered by suboptimal rearing technology for edible grasshoppers. Additionally, the overall value chain for crickets remains underdeveloped (Tanga et al. 2021). The limited incorporation of these insects as ingredients into animal feed may be attributed to the dwindling number of farmers engaged in their cultivation, coupled with their widespread use as food immediately after being collected from the wild (Paul et al. 2016; Tanga et al. 2021). Finally, crickets are vulnerable to bacterial infection (e.g. *B. bassiana* or *Metarhizium anisopliae* (Metchnikoff) Sorokin) and these events led to temporary closure by farmers of their cricket farms in Kenya and Uganda (Flying Food 2023).

2.4 Coleoptera

Beetles constitute the most numerous orders in the living world, with 25% of all eukaryotic species belonging to Coleoptera. Notably, they also represent the most significant group of edible insects globally, with over 500 species consumed (Le Gall 2016). Most edible beetles are larvae of xylophagous species, primarily Cerambycidae found in dead wood, as well as species developing in decaying Palmaceae, such as the African Palm Weevils (*Rhynchophorus* sp. Herbst) or Dynastidae larvae from *Oryctes* sp. Hellwig. In Central Africa, *Augosoma centaurus* (Fabricius) is also a consumed species (Fogang Mba et al. 2018) along with *Sarothrogastra edulis* (Karsch), an endemic Cerambycidae from the island of Sao Tomé (Nève et al. 2022). Despite their hardness, adults are consumed in various places, including adults of the *Sternocera* sp. Eschscholtz (Buprestidae) in Benin and Botswana as well as *Pachnoda* sp. Burmeister (Scarabaeidae) in Benin and Cameroon (Riggi et al. 2016).

2.4.1 Palm weevils

Rhynchophorus spp. is a type of beetle causing damage to palm trees, particularly in Southeast Asia and Africa. In Africa, *Rhynchophorus* is represented by at least two species, *R. phoenicis* (Fabricius) and *R. quandrangulus* Quedenfeldt. *R. quadrangulus* is mainly distributed in high elevation region, Fouta-Djalon in the Republic of Guinée, West and Northwest region of Cameroon, while *R. phoenicis* is widely spread in Africa. They live together in the highlands on the same *Raphia* species. *R. quandrangulus* is living on different palm tree species (principally oil and Raphia) and on Coconut Tree (Muafor et al. 2015). In Cameroon, advancements in the rearing of *R. phoenicis*, as highlighted by Muafor et al. (2015) have shed light on potential practices. However, there is a need for the consolidation of rearing methods to make them more affordable for a broader audience. Presently, the available method relies on the use of raphia tissue, necessitating basic knowledge about *Rhynchophorus* collection. Experiments have also been conducted in Gabon, Ghana, Liberia, and the Democratic Republic of Congo, demonstrating successful and economically viable breeding practices (Reynolds et al. 2022). As an example, the economic viability analyses done by Commander et al. (2019) in Ghana indicate that active farmers can achieve a break-even point and successfully repay their $180 loans by producing 3020 larvae at a unit selling price of $0.028. This is accomplished within a specified timeframe of 4 months and 7 days (17 weeks). Over the course of a year, each farmer undergoes three production cycles, resulting in a cumulative revenue of $543.98. The average monthly production of 755 edible larvae contributes to a net cash availability of $260.98, with a projected net profit of $80.78 anticipated in the inaugural year of production.

2.4.2 Tenebrionidae

The extensive diversity within the Tenebrionidae family, boasting over 30,000 species, presents numerous opportunities for substrate recycling (Salazar-Sánchez et al. 2022). However, in Africa, the documentation of Tenebrionidae remains limited, necessitating comprehensive fauna, taxonomic, and ecological studies. The genus *Tenebrio* is well diversified with fifteen species belong to the endemic subgenus *Tenebrio* (*Afrotenebrio*) Gridelli. There also two monospecific subgenera, *Tenebrio (Curacurvamtenebrio)* with *T. (Curacurvamtenebrio) kamgangi* Robiche from Gabon and *Tenebrio (Megatenebrio)* with *T. (Megatenebrio) giganteus* Fairmaire from East Africa (Bouchard et al. 2021). Two species, *Tenebrio (Tenebrio) molitor* and *Tenebrio (Tenebrio) opacus* native from the European continent become also acclimatized in Africa (Delobel & Tran 1993). Most of these species typically inhabit dead wood and tree cavities, while some of them have been able to adapt themselves to seed stocks and become pest species, as *T. molitor* (Delobel & Tran 1993).

Tenebrionidae, notably *T. molitor*, have been studied for their ability to consume various types of plastics, including polystyrene, polyurethane, polyethylene, polylactic acid, and polyvinyl chloride (Kuan et al. 2022). This research is particularly relevant given the significant environmental concerns associated with plastics in Africa (Akindele & Alimba 2021).

3 America

3.1 North America

A quick dive into the history of indigenous communities throughout the Americas demonstrate that insects have long been part of the human diet (Schrader et al. 2016). So, technically, society is rediscovering its roots in native culture but also nature. Rising interest in backyard farming has boosted attention given to insect production. Part of the reason involved the Covid-19 pandemic, which disrupted food supply chains, and increased domestical food production across the globe (Attia et al. 2022). At the same time as interest in sustainable food production increased, the same also occurred for health and wellness trends among consumers in North America, benefits offered by insect production. At present time only the black soldier fly is permitted as ingredient in animal feed in North America (US-FDA 2023a). Canada has allowed the house cricket and the yellow mealworm as ingredients for pet food such as cats and dogs (Larouche et al. 2023). This is currently limiting the North American market for mealworms and crickets to feed for exotic pets, bird feeding, and for zoo animals. However, processed house crickets and mealworms in the form of powders for human consumption are not currently regulated. Processed insects are allowed as additives of ingredients of food if the manufacturing processes follow current good manufacturing practices (CGMP) (Larouche et al. 2023). The CGMP are defined as following clean and sanitary conditions devoid of toxic chemicals and human pathogens (US-FDA 2020). Allowance for introducing insects as food to the North American market requires that insects to be generally recognized as safe (GRAS) by the FDA (US-FDA 2023b). This recognition as GRAS can be attained by two methods: 1) through experience based on common use in foods with a substantial history of consumption as food by a significant number of consumers or 2) through scientific procedures with sufficient quantity and quality of scientific evidence as required for approval of substances as food additives (US-FDA 2023b). Because there is not long history of insect consumption in North America, GRAS recognition can be only obtained through scientific procedures. This process can be costly and, in general, is out of the reach of small companies. Although there are existing programs to fund projects for small companies in the US and Canada, these programs are highly competitive and rarely accept proposals associated with regulation issues. It is important for the scientific community to recognize this potential hurdle and to focus efforts to satisfy FDA requirements for insect products to be utilized as food and feed.

3.1.1 Canada

In 2020, at least 28 companies were producing insects in Canada (Cohen & Duchemin 2020). In general, crickets and mealworms are produced for human consumption, whereas BSF are produced for animal feed (Cohen & Duchemin 2020). In Ontario, two companies have received large investments. The first, Entomo Farms, was founded in 2012 and is in Norwood. To date, they have secured $2.9 million in funding (Peel 2021) and their product line consists of cricket flour (among others for a US dog food supplier, Jiminy's), whole roasted crickets, and cricket snacks. The second company, Aspire Food Group, is a US-based company that launched in 2013 in Austin, Texas. They raised $49 million in funding between 2017 and 2019 and broke ground on construction in London in 2020 (Aspire 2023). The facility in Canada was completed in 2022 and reportedly produces 9000 metric tons of crickets each year (Dras 2022). Super Cricket Farms (founded in 2009) in Saskatoon (Saskatchewan) offers different species: live crickets and mealworms. Among the mealworm producers, 12 companies were listed by Cohen et Duchemin (2020) but no large investments were made. It appears that crickets and BSF are receiving more funding than mealworms in Canada. Regarding BSF, major companies consist of Enterra Feed Corporation (founded in 2007), Oreka Solutions (2014), Entosystem Inc. (2016), and Oberland Agriscience Inc. (2017). Among these, Entosystem Inc. has raised over $52 million though, the largest insect facility at one time in Canada belonged to Enterra (17500 m^2), which raised $10 million by 2018 (Burwood-Taylor 2018). Enterra was also the first to receive approval from the Canadian and US governments to produce BSF as feed for salmonids (Fish Site 2018).

3.1.2 United States of America

There are at least 11 cricket companies in the US offering an assortment of products. Concerning the funding, All Things Bugs (founded in 2011) in Oklahoma City has received 5 million in research funding (All Things Bugs 2023). Another cricket farm, Chapul Farms (founded in 2012) in McMinnville, Oregon, has secured over $2.5 million (Regenerative Food Systems 2022). Like Canada, some businesses sell more than one insect species. For example, Chapul Farms produces crickets and BSF. Others sell mealworms and crickets (e.g., TopHat Cricket) or all three species (e.g., Fluker Farms). Regarding mealworms, to date, there are at least 13 companies growing mealworms. Large investments have been made to expand mealworm production in the US. For example, Beta Hatch (founded in 2015) raised closed to $10 million by 2020 and recently opened a large mealworm facility (50,000 ft^2) in Cashmere (Kerwin 2022). Even outside of North America, financial support has been awarded to expand mealworm production in the US. Particularly, Ÿnsect, a French-based company founded in 2011, has raised over $500 million to produce mealworms and recently opened a facility in Nebraska (Ÿnsect 2022). Substantial investments have also been made toward the industrialization of BSF. Currently, there are at least 10 companies rearing BSF or selling BSF products in the US. Remarkably, the world's largest insect protein facility is expected to be completed by the end of 2023 in Decatur, Illinois by Innova Feed, a French-based company (Innova Feed 2023). Currently, they have two production sites in France, with the highest production capacity in the world, and expect to produce 60,000 metric tons of protein, 20,000 metric tons of oil, and 400,000 metric tons of fertilizer at their US site (Innova Feed 2023).

Insect producing companies in the US have been successful obtaining grants and interesting investors to develop and grow the industry. As a result, many new companies have been created with good financial support (Dossey et al. 2016).

3.1.2.1 Yellow mealworms

Although *T. molitor* has been produced commercially in the US for more than 60 years, the industry has experienced a transformation within the last 10 years changing its focus from exotic pet feed and bird feed to human food ingredients and animal feed. Commercial success of *T. molitor* marketed as exotic pet feed has been due to its high price. While the relatively high price of *T. molitor* powder is still acceptable within a limited market for human consumption, the success of this product as animal feed will require a substantial reduction to become competitive. Moreover, now, insect production is not able to supply the required volume of protein to become a viable alternative (Nassar et al. 2023).

The basic diet of *T. molitor* in most of the industrial settings consists mainly of wheat bran (Morales-Ramos et al. 2023). One important advantage of using wheat bran as feed is that this ingredient is widely and reliably available in large quantities. However, wheat bran is not a cheap ingredient and at its current price of approximately $0.22 US dollars per Kg. For this reason, there has been increasing interest in evaluating agricultural and industrial by-products as sources of feed (Morales-Ramos et al. 2023). Agricultural by-products can provide a good source of nutrition for *T. molitor* at a lower cost but are not always widely available at industrial volumes and could lack the composition consistency that wheat bran offers. Based on methods developed to produce optimal insect diets, it will be necessary to develop a data base with information on 1) the by products available; 2) region of availability, and 3) nutritional profile.

The current rearing systems for production of *T. molitor* rely on the use of trays where larvae grow to the commercial size or complete development if used for reproduction (Cortes Ortiz et al. 2016). Trays need to be of a dimension that can be handled with relative ease, restricting the number of larvae. Hundreds of thousands of trays may be required to achieve the production goals and they need to be serviced regularly to provide food and water to the larvae (Cortes Ortiz et al. 2016). Trays will require washing at the end of the production cycle and transportation to the required site for the start of a new production cycle.

There is insufficient knowledge on the optimal conditions for the growth and reproduction of *T. molitor* principally due to the long length of this lifecycle. The use of an inefficient rearing system combined with the use of suboptimal environmental conditions can contribute to reduce productivity and increase production costs (Cortes Ortiz et al. 2016). Nevertheless, the fact that a lightly rentable industry exists with the current rearing conditions is encouraging. To allow the development of the insect industry, different gaps in knowledge must be addressed. For example, a fundamental aspect of insect agriculture for which microbiology, entomology, genetics, and life histories of the insects feeding on food sources, such as pre- or post-consumer food waste and other organic substrates, is not well understood. To address these, and other gaps in the growing industry, there is a requirement for increases in infrastructure and regulatory frameworks.

3.2 Central and South America

3.2.1 Current situation

In several Latin American countries – including Brazil, Ecuador, Colombia and above all Mexico (dealt separately below) – entomophagy is widespread, principally among members of indigenous and local communities where small-scale production is the most common (van Huis et al. 2013). In Latin America, there are approximately 50 million indigenous peoples, about 10% of the total population. Other ethnic groups include European-Amerindians (Mestizos), Afrodescendants, and Mulattos (United Nations Development Programme 2013). A large portion of these indigenous peoples and traditional communities throughout Latin America rely on local resources for their survival, and insects have been part of their diet for a long time (Costa-Neto 2015). That is the reason why insects and their creation are mostly oriented towards human consumption. At least in these indigenous cultures, insects are not collected or raised to feed livestock.

Small-scale commercial insect production has developed over the past decade and involves mass production of *A. domesticus, H. illucens*, and *T. molitor*. Commercial producers include start-up, as well as spin-off, and venture companies. Finally, through livelihood economy initiatives rural communities produce insect species such as BSF to feed to their livestock and thereby reduce the cost of commercial feed and produce bio fertilizer. Two such initiatives are the Colombian Initiative Insects for Peace (I4P) and the project titled "Sustainable fish farming using alternative foods in the Peruvian Amazon" (Barragán-Fonseca et al. 2022).

Medium and large-scale insect production is carried out for commercial purposes and focused on four species: *A. domesticus, Gryllus assimilis* (Fabricius), *H. illucens*, and *T. molitor*. Medium-scale companies produce principally for local sale and large-scale companies principally for export. Based on an internet search as well as information provided by the Latin American Association of Animal Production (ALPA), the greatest number of medium and large-scale insect producing companies are established in Mexico (27), Brazil (14), Chile (7), Argentina (5), Costa Rica (5), Colombia (4), Peru (4), Guatemala (2), Uruguay (2), and Cuba (1). The majority of these companies produce insect-based products solely for human consumption (Bermúdez-Serrano 2020). In Colombia, 22 small companies and other initiatives produce insects for both human food and animal feed. Most (44%) produce BSF; the others produce one or more of a variety of species – mealworms, crickets, cockroaches, principally for animal feed (Barragán-Fonseca et al. 2022).

In Mexico, traditional insect production involves cultivating species traditionally used by indigenous communities as this provides greater yields than simply gathering those naturally existing in the local environment such as grasshopper (*Sphenarium purpurascens* Charpentier) (Piña-

Domínguez et al. 2022). Compared to other American countries, the market for insect production in Mexico leans more towards insects as food. In fact, among the 735 species of edible insects in Latin America, Mexico consumes 602 (or over 81.9%) of them (Abril et al. 2022). In Mexico, edible insects are a daily food in the diet of many rural communities and this traditional habit has been known and transmitted since Pre-Hispanic times and transmitted orally from parents to children (Ramos-Elorduy 1997). Most of the insect species consumed are collected during their season of abundance directly in ecosystems using nets, entomological tweezers, vacuum cleaners, "machetes" or hands. Several species are also semi-domesticated such as the "escamoles" (*Liometopum apiculatum* Mayr and *L. occidentale var. luctuosum* Emery). One kilo of "escamoles" from Puebla cost is around US$ 55 where few families are dedicated to collecting these insects. Research in the highlands of San Luis Potosi and Zacatecas found 77 nests producing 394.37 kilos of "escamoles" during a period of abundance (Figueroa-Sandoval et al. 2018). Other species from the Hymenoptera order are semi-domesticated such as various species of wasps of the genera *Polistes, Polybia, Brachygastra, Mischocytarus* and *Vespula* as well as stingless bees of the genera *Melipona, Trigona, Cephalotrigona* or *Trigonisca* and in other orders, "white maguey worm" (*Aegiale hesperiaris* (Walker) Lepidoptera: Hesperiidae), "Jumiles" (*Edessa* spp. and *Euschistus* spp. Hemiptera: Pentatomidae) or grasshoppers (*Sphenarium purpurascens* Charpentier) (Katz 1996). The diversity of semi-domesticated insects demonstrates the potential for insects to be raised on an industrial scale in Mexico, but which still requires a great deal of research, as well as the dissemination and exchange of existing knowledge between rural and urban communities.

Compared to Canada and the United States, there is less financial support for expanding or growing the insect farming industry. Nevertheless, some companies are in high development such as Nutrinsectos, which rears and sells both crickets and mealworms since 2013 in Guadalajara (Watson 2021). In the State of Mexico, a developing company is dedicated to the production of crickets and produces annually 4,032 kilograms of dry crickets (equivalent to 13,440,000 crickets) marketed for pet food and for human snacking (Personal communication with Covarrubias Esquivel 2023). Interestingly, in 2014, Aspire's founders initially established themselves in Mexico, Ghana, and Texas, USA. They received $1 million non-debt seed capital and determined that it was easier to conduct research and development in the US and aimed to perfect cricket farming before opening a facility in Mexico (Linknovate 2019). The French company Ynsect is now producing mealworms in Mexico and Optiprot (founded in 2016) is also producing mealworms for food and feed in Cuernavaca, Morelos. Concerning BSF, only one company (called Dipterra) located in Leon, Guanajuato, was found to offer pet food for reptiles, fish, birds, and other exotic animals (Dipterra 2023).

In addition, the following companies are known to produce and/or process edible insects in Mexico: Bug biter corporation (edible insects as food and feed), CrilloMX (dried crickets and cricket powder), Giiga MX (crickets and mealworm), Gryum (cricket powder), Merci mercado (grasshoppers, white and red maguey worm), Orbitaverde (insect-based snacks, mealworm for pet foods and frass), Entomovit (cricket powder), Bug Box (mealworm, BSF and crickets) and Entomolove (BSF).

3.2.2 Prospects for insect production

One of the main concerns in the Latin American insect industry is the lack of regulation. Most Latin American nations lack a regulatory framework regarding insect breeding and processing for sale (Espitia Buitrago et al. 2021). Nonetheless, some – including Brazil, Argentina, Colombia, Chile, and Costa Rica – have started working on some regulation concerning biosecurity of insects and their by-products. For instance, in Brazil in 2021, the following species and forms of processed food insects were officially approved for use as feed or food, depending on the specific case (Mapa 2021): cinerea cockroach (*Nauphoeta cinerea*), *H. illucens, G. assimilis, T. molitor*, and *Z. morio*. In Argentina, new foods are then incorporated into the Argentine Food Code (CAA), with edible insects being specifically included in Chapter XXIII – Edible Insects. In Peru, the mealworm company Demolitor is taking the lead in this area in their country, and they have achieved specific regulations for the production and sale of products based on *T. molitor*. In Colombia, the technical institute responsible for implementing government policies regarding inspection, surveillance, and sanitary control – INVIMA, has approved the use of meal from *G. sigillatus* species as a human food ingredient. The National University of Colombia, in collaboration with the Ministry of Agriculture, is conducting research aimed at expanding the use of insect species as food and establishing regulations regarding insects in animal feed. Collaboration involving the government, private sector producers, and associations like ALPA, and the academy is needed to identify and develop insect value chains and promote the development of a regulatory framework (Dicke et al. 2020).

In 2014, 735 species of edible insects were systematically identified in Latin America (Data Basin 2023). Given the great diversity of insects in the region, these is a need to collect and identify new species that could match or exceed the potential of those conventionally used in the industry. For instance, the yellow soldier fly (*Ptecticus trivittatus* (Say)) of Colombia, a Stratiomyidae species which has a larva like that of BSF and feeds on organic waste, may be an interesting species to explore as animal feed (Personal communication with Barragán-Fonseca 2022). Bioprospecting insect species – consisting of the exploration of insect species that could be developed into commercially valuable products – is one possibility for growth of the insect industry. However, given the lack of clear rules and guidelines regarding investigation, use and equitable exploitation of natural resources, legal issues may arise with respect to bioprospecting insect species. Many current environmental, trade, and geographically-specific agreements are incomplete or ambiguous with respect to bioprospecting biodiversity (Srivastava 2017). There is a need to establish regulations for an adequate collection to assure sustainable use and conservation of wild edible insects.

4 Asia

In many Asian countries, insects are eaten as snacks or included in traditional dishes. Some examples include local delicacies like deep-fried crickets in Thailand, boiled silkworm pupae (*boendaegi*) in Korea (Meyer-Rochow et al. 2019), stinkbug (*Tari*) in India (Ghosh et al. 2021), grasshoppers (*jajabuse*) and yellow jacket (*hebo*) in Japan (Nonaka 2014). People ingest insects as a planned part of their diet, and it is neither accidental nor due to food scarcity. In general, entomophagy is considered as a delicacy among the communities which are familiar to have insect foods and is a cultural attribute to many traditional communities, even today. As an example, preparation of food using red weaver ant broods (vernacular name: *Aamlori-tup aru koni*), and consumption during *Bohaag Bihu* festival in Assam (India) is an essential part of the celebration. Despite a rich tradition of eating insects in many communities it has not received much attention until the 1980s.

4.1 Commercial farming

There has been growing interest in the edible insect industry in Asia, driven by the increasing demand for sustainable and nutritious food source. Several start-ups and companies are now exploring the commercial potential of edible insect. For example, Thailand based firm “Bugsolutely” produces snacks made from cricket flour, Malaysia based “Ento” offers a range of insect-based food such as burgers and energy bars. Many small-scale commercial farming facilities also coming up in Asia for the animal feed market. For instance, there were 20,000 farmers in Thailand involved in cricket farming (Hanboonsong et al. 2013) and in India, many small-scale BSF farms produce insects to supply the local poultry farms. Comparatively large farms play significant roles not only in improving the capacity of higher production but also it could help in the formulation of legislation and product development.

4.2 Semi-domestication

Although there is a lack of comprehensive documentation on the socio-economic status of individuals engaged in the collection and sale of edible insects across Asian countries, it can generally be observed that these activities may provide an additional source of income for households. For instance, Mozhui et al. (2023) conducted an extensive survey to assess the impact of the edible insect sector on the socio-economic conditions and livelihoods of both rural and urban communities participating in these endeavors in Nagaland, India. The findings revealed that 25% of the sellers earn more than US $50.07 per day, 8% earn between US $25.04 to 50.05 and US $12.53–25.03, 34% of sellers earn US $6.27–12.51, and 25% of sellers earn about US $0–6.26 per day.

4.2.1 Palm weevil

Palm weevils (*Rynchophorus* spp.) semi-domestication is a common practice in Thailand, Indonesia, and Malaysia (Hanboonsong et al. 2013). Hanboonsong et al. (2013) stated that 120 farmers produced 43 tons of palm weevil larvae in 2011. Palm weevil semi-domestication typically involves the collection of wild larvae from palm trees and rearing them using specialized containers or baskets, where the larvae are fed a diet of palm trunk or other suitable food sources until they pupate and emerge as adults. The adults can then be used for food or sold for commercial purposes. Palm weevil feces are a by-product of the process sold as an organic fertilizer. Semi-domestication of palm weevils needs to be improved and this includes research on optimal feeding regimes, breeding strategies, and disease prevention measures.

4.2.2 Weaver ant

Oecophylla smaragdina (Fabricius) have been semi-domesticated for their ability to control insect pests in agricultural crops, particularly in fruit orchards. Farmers allows weaver ants to live and nest in fruit trees (e.g. mango, papaya, or durian trees), a practice known as “ant agriculture” (Offenberg 2011). The ants then protect the trees from pests such as fruit flies. The farmers may also provide supplemental food and water for the ants to encourage their presence and activity. Besides the use as biological control agent, weaver ants are used as food, feed, and medicine (Chakravorty et al. 2016).

4.2.3 Wasps and hornets

In Japan, China, and some northeastern part of India, *Vespa mandarinia* Smith is traditionally reared for its larvae (Nonaka 2010). Nonaka (2010) provides a description of the hunting and semi-cultivation process of *Vespula* that include the location of the nest using fresh bait (e.g., fish, animal flesh) to attract workers, capturing a queen and her workers in the wild and housing them in a special enclosure designed to mimic the hornet’s natural habitat and includes a nest made from paper or wood pulp. Hornets are fed a diet of honey or sugar and water, as well as other insects (Kiewhuo et al. 2022). The hornet larvae are harvested when they are about two weeks old and are consumed raw or cooked.

4.3 Domestication

4.3.1 BSF

Vietnam, Taiwan, Malaysia, and China are exploring the treatment of waste (livestock feces or other residues) for biodiesel production and animal feed through defatting processes of BSF. In Japan, the emphasis is on waste management as well as using BSF as animal feed. The Republic of Korea is primarily investigating the BSF-derived metabolites including the activities of substances and biochemical properties of digestive enzymes. Finally, most countries are studying the rearing techniques for BSF as an industrial resource.

4.3.2 Cricket

Two species of crickets (*A. domesticus* and *G. bimaculatus*) are generally farmed. Filed cricket *Teleogryllus testaceus* (Walker) is also receiving attention (Halloran et al. 2018) and *Teleogryllus emma* (Ohmachi & Matsuura,) in Korea (Ghosh et al. 2017). Concrete cylinder pens, concrete block pens, plywood boxes, plastic drawers are generally used as breeding containers (Hanboonsong et al. 2013). Halloran et al. (2018) show that the most common rearing systems in Thailand consist of rectangular concrete block pens with an average size of 7.67 m^2. Nylon netting is used to cover the pens to prevent the insects from escaping and it helps to prevent predator entry. Similar farming system is also found in Cambodia with bigger average pen size (5×2 m^2). Farmers place egg cartons inside the pens to offer shelter to crickets and to facilitate the egg laying. In Lao PDR, rearing systems also include small cylindrical pens, rectangular wooden boxes, plastic sheets and gypsum boards. Commercial high protein animal feed, particularly chicken feed, is generally used as cricket feed (Halloran et al. 2018). In Laos, cricket farmers typically employ formulated chicken feed with around 21% protein content to promote cricket growth. In Cambodia, there is a growing trend of using brown rice flour, which can substitute up to 75% of the chicken feed to reduce production costs (Halloran et al. 2018). A study by Caparros Megido et al. (2016) indicates that a diet consisting of 80% cassava leaf powder and 20% brown rice can effectively supplement a traditional chicken feed-based diet, resulting in crickets with substantial body mass. When crickets reach two weeks, food supplement including local fruits (e.g., jackfruit or watermelon) and plant leaves (e.g., cassava or taro) are generally added.

4.3.3 Mealworm

The yellow mealworm has been reared and commercialized as an alternative protein mainly for fish, pets, chicken and even for human. There are several mass-rearing companies in Asia such as Keil Co. (Korea) and Hao Cheng Industry (China).

4.4 Current scenario of edible insect industry in different Asia countries

4.4.1 China

Ding et al. (1997) documented more than fifty insects used as therapeutic agents for several symptoms. Hao Cheng Industry, TOPU bioscience, Guangzhou Unique Biotechnology operates the commercial insect producing facilities. They farm mealworm, BSF, cricket and produce animal feed. In addition, there are several small to medium scale insect farms.

4.4.2 India

The farming of insects as animal feed is a very new entrant in the agriculture. Currently, several commercial start-ups are coming up which are rearing BSF for producing animal feed. Besides, there are several small-scale farms rearing BSF for their own poultry farms or crickets and cricket flour for human.

4.4.3 Japan

Since 2010, many start-ups are coming up which are engaged in the production of edible insects, making food products incorporating insects such as snacks, ramen (noodles) etc. To cite a few examples, Ellie (since 2018) from Tokyo University, produces foods and beverages using silkworm larvae or Futurenut (since 2019) from Takasaki University, sells a range of cricket-based products like cricket flour or crackers. Several restaurants also serve foods made up of edible insects. Takeo serve cricket pasta and silk moth tea at their restaurant in Tokyo. Another restaurant in Tokyo, Antcicada (since 2020), serves cricket-based ramen and cricket soy-sauce. Mog bug is a brand of insect-based products vending machines, operated by Asia Tokyo World Co. Ltd.

4.4.4 Korea

Korea registered 10 insects as edible such as silkworm pupae (*B. mori* and *B. batryticatus* L.), dried larvae of *B. mori* infected by *Beauveria bassiana*, mealworm larvae, white spotted flower chafer larvae (*Protaetia brevitarsis* Lewis 1879) or honeybee pupae (*Apis mellifera* L.).

In South Korea, there is a considerable number of insect rearing farms, totaling 2,318 farms as of 2018, with the majority of these being characterized as small to medium-sized operations (Rural Development Administration 2020) (Rural Development Administration 2020). Nevertheless, KEIL stands out as one of the largest automated smart farms in the nation, boasting a production capacity of 2,000 tons of mealworms per year, and it has set a goal to increase its annual output to 15,000 tons by the year 2025.

4.4.5 Thailand

Thailand stands in the frontline for the cricket production in the world. JR Unique, Starbugs Insect, Bugsolutely, Global

Bugs Asia are pioneering commercial insect food companies and produce a wide range of insect based human food. Although several packaged processed insects including dry insects, pasta, and snacks are in the market now a days, still it is far from the mainstream foods (Reverberi 2021).

4.4.6 Singapore

Several commercial companies, including Nutrition Technologies, Protenga, Insectta, and Entobel, are involved in rearing BSF for animal feed, with the added benefit of producing insect frass as fertilizer. Insectta goes beyond, also producing chitosan and melanin as biomaterials. Notably, Hermetia BioScience operates a production facility on Sumatra and innovatively uses empty fruit bunches from the palm oil industry, a significant side stream accounting for up to 40 million tons in Indonesia and up to 25 million tons in Malaysia, as a diet for BSF. This approach addresses environmental concerns associated with the burning and rotting of empty fruit bunches, which lead to pollution and methane release. By bioconverting these side streams into BSF diet and utilizing the frass as an alternative biofertilizer, the palm oil production process can become more sustainable (Klüber et al. 2022). Hermetia BioScience is also developing cosmetics and other higher added value insect-derived products. Finally, Singapore will host the next “Insects to feed the world” conference in June 2024.

4.4.7 Vietnam

Republic of Korea, Thailand and Vietnam are granted permission to export edible insects to the countries in the European Union under regulation (EU) 2021/405. Entobel is a Singapore based company with a BSF production facility in Vietnam (Tri 2023). Another UK based company; Cricket Hop Co. are rearing cricket is Vietnam. On the other hand, Cricket One rears cricket and produces a wide range of insect based human food, animal and pet feed, and fertilizer (The cricket hop Co 2023).

4.5 Legislation of edible insects in Asia

Regulation of edible insect production in Asia exhibits variations from one country to another. In Thailand, where there is a longstanding tradition of consuming insects as a protein source, the government has established regulations and standards to ensure safety and quality. The Department of Livestock Development has issued guidelines for the production and sale of edible insects, encompassing requirements related to hygiene, food safety, labeling, and packaging. Notably, specific standards for cricket farming have been developed, particularly with the aim of meeting the criteria for accessing the EU markets (Preteseille et al. 2018). In China, there are regulations for the production and sale of edible insects. The China Food and Drug Administration (CFDA) is taking care of the guidelines for the production, processing, and marketing of insects as food (Feng et al. 2018). In Japan, novel foods produced by traditional methods do not require pre-market authorization (Lähteenmäki-Uutela et al. 2021). Food safety is under the responsibility of the Ministry of Health, Labor and Welfare (MHLW) while the Ministry of Agriculture, Forestry and Fisheries (MAFF) oversees the Act on Safety Assurance and Quality Improvement of animal feeds, which includes the maximum limits for pesticide residues, heavy metals, mycotoxins and melamine. Feed manufacturers, importers and/or dealers must submit notification to the MAFF prior to starting a business. In contrast, in other Asian countries, such as Vietnam and India, the regulation of edible insect production is less developed. However, as Vietnam is one of the countries approved by European Union to export their edible insects, they facilities are required to comply the specification recommended by EU. Recently India has focused on the use of edible insects as animal feed and several commercial facilities are comping up but, as of now, no legislation frame has been developed yet.

5 Australia

Despite entomophagy has been practised in Australia for tens of thousands of years by Indigenous nations (Ghosh et al. 2021; Yen 2005), the interest in insects by modern Australians is only rising, first with the development of the ‘bush tucker’ cuisine. In 2008, *Z. morio, A. domesticus*, and *T. molitor* were included in the Australia New Zealand Food Standards Code as non-traditional, not novel food, allowing the sale for human consumption of food products containing those insects as ingredients (FSANZ 2023). In 2019, *O. smaragdina* was recognised as an indigenous food (FSANZ 2023). Beetles, grasshoppers, butterflies, moths, bees, bugs and dragonflies may also be consumed, although they are not allowed to be sold as food (Lähteenmäki-Uutela et al. 2021). In terms of farming insects, Australia regulates the importations of insects for either human consumption or animal feed: the insects must be dead and heat-treated with supporting documentation and the species must not be listed on the CITES list of endangered species (Nolet 2020). Since certain insect species are declared as pests in different states across Australia, insect farmers require written approval, from their relevant authority, for each insect species farmed. Currently there are no regulations to commercially reared insects in Australia. While for insects used for human consumption the regulations include: the species included in the Australia New Zealand Food Standards Code; the need that all insect products sold in Australia must comply with specific standards on cleaning and hygienic practices. It is also required by law that insect products clearly label whether the food was grown, produced, made in, or packaged in Australia. Currently there are no regulations in terms of the processing of insect products. BSF is not approved for human consumption and is the only species investigated for feed. Insect protein is allowed as feed for livestock (aquaculture and poultry) and pet food markets under the regulations of the Australian Pesticides and Veterinary Medicine Authority (Lähteenmäki-Uutela et al. 2017). Products are sold online, in pet stores, and supermarket retail channels (Nolet 2020). BSF producers mostly use organic waste as substrate to produce feed and frass. Goterra (BSF and mealworms) pioneered automated insect farming in Australia as a solution for waste management through the creation of scalable, modular insect farms that process waste at its source, minimizing transportation expenses. The company is also extending its efforts to handle packaged food waste.

In 2017, the Insect Protein Association of Australia (IPAA) was formed to support insect farmers and, at the end of 2022, it had 57 members (from those, 42% represent primary producers, consultancies, and downstream 'value-add' businesses) (IPAA 2023). Species currently mass reared are crickets, mealworm beetles and BSF. Other species with commercial rearing potential include the super mealworm (*Z. morio*), wood cockroaches (*Nauphoeta cinerea* Olivier 1789) and silkworms (ARC Ento Tech Ltd 2023). Currently, there are seven BSF producers, three cricket producers, and one BSF, cricket and wood cockroach producer associated with the IPAA. Also, there are eight consultants, four product developers (including for pet food) and one aggregator (IPAA 2023).

The Australian insect industry is still in its early stages of development but has the potential to grow into a $44 M opportunity with the right strategic technology investments (CSIRO 2022). Edible insects are currently sold directly to the consumer or formulated (e.g., chips or pasta enriched with crickets) and they can be found online and in selected shops and restaurants (Nolet 2020).

5.1 Challenges

In Australia, the potential for mass-rearing edible insects faces several challenges that must be addressed for the industry to thrive. These challenges can be broadly categorized into five areas: lack of capital, absence of reliable and affordable substrates, regulatory ambiguity, limited consumer acceptance, and the need for Research and Development. The majority of edible insect businesses are small startups, which can make it difficult for the industry to meet consumer demands. The shortage of capital hampers access to technology and equipment, limiting scalability and processing capabilities for producing high-quality protein meal and oils (Nolet 2020). Despite Australia's robust agricultural sector, certain by-products of food and beverage manufacturers, which could serve as reliable, affordable, and consistently high-quality substrates for the insect industry, have already been monetized as feeds for intensive livestock production, rendering them less accessible for insect farming.

Guidelines are needed to instruct insect farmers about issues such as production quality control, biosecurity or occupational health and safety (Ponce-Reyes & Lessard 2021). Regulatory clarity and consistency between Australian states and territories, especially for insects as livestock feed would help the industry continue to grow as regulations sometimes vary between states (Nolet 2020). The pet food industry in Australia, however, is currently self-regulated and Australian insect farmers that sell into this market are open and transparent about the quality and safety of their products (IPAA 2023).

Another challenge is the negative perception of insects as food (Nolet 2020). In Australia, the perception of edible insects as a viable food source is mixed, partly due to the lack of familiarity with edible insects as a food source (Wilkinson et al. 2018). While some people are open to the idea of consuming insects (Hopkins et al. 2022), others are sceptical (Wilkinson et al. 2018) or have raised ethical concerns (e.g., locations of insect farms, ethics of certain processing methods) (Nolet 2020). In recent years, more people in Australia have become aware of the potential benefits of consuming insects. As a result, more companies have emerged (e.g., Circle Harvest, GrubsUp and Hôppa) and are increasing their production of edible insects for human consumption. Circle Harvest's production, for example, recently increased their capacity to grow 10,000 kg of edible insects/week from 200 kg (Waters 2019).

Finally, there is a need for research across various domains. Scientific publications on large-scale insect production and optimal production conditions, such as feed and temperature, are limited, particularly for native species. Supplying founder populations for research colonies can pose a financial challenge for farmers, compounded by a lack of incentives (i.e., no available funding or perceived benefits). Consequently, scientists often rely on their own highly lab-adapted research colonies, which may differ from the strains used in commercial operations (Nolet 2020). Trust issues exist concerning collaboration between researchers and companies for joint investments in research, either as cash contributions or in-kind. Further research is essential to support the development of new technologies, especially in food processing, to ensure consistent high-quality protein meals and oils. Integration of automation, sensing, machine learning, and artificial intelligence also requires additional investigation. Additionally, research in biosecurity, addressing potential disease outbreaks, and the (cryo-)preservation of commercial lines can assist the industry in optimizing growing conditions for improved characteristics (Ponce-Reyes & Lessard 2021).

6 Europe

In 2013, insect rearing companies within the European Union (EU) identified legislative challenges hindering the insect industry's development. Consequently, they established the International Platform of Insects for Food and Feed (IPIFF) in Brussels. IPIFF, a non-profit organization, represents the interests of the insect production sector to EU policymakers, European stakeholders, and citizens. IPIFF played a crucial role in securing EU approval for using insects both as food and feed. In 2017, the EU allowed the use of insect proteins in aquafeed, and since September 2021, the use of insect-processed animal proteins has been authorized in poultry and pig feed. (Fig. 1).

In Europe, the production and sale of insects as food are regulated by the 'Novel Foods' legislation, specifically Regulation (EU) No 2015/2283. This regulation covers whole insects, parts of insects, processed insect ingredients (such as insect powder), as well as ingredients derived from sources other than whole insects, such as insect extracts. Companies involved in insect production require prior authorization from the European Commission (EC), endorsed by EU Member States, to market their products across the

Insect species admitted for feed in EU (Reg. 893/2017 and 1925/2021)

... *Achetadomesticus* ... *Bombyxmori* ... *Gryllus assimilis* ... *Musca domestica*
... *Alphitobiusdiaperinus* ... *Gryllodessigillatus* ... *Hermetia illucens* ... *Tenebrio molitor*

Insects as feed EU **Reg. 68/2013** Catalogue of feed materials in accordance with **Reg. EC 999/2001** and Reg. EC 1069/2009	Ruminant animals 	Poultry 	Pigs 	Aquaculture 	Pets 	Fur and other animals 
Insect proteins (entry 9.4.1, Processed animal proteins)	✗	✓**	✓**	✓**	✓	✓
Insect fat (entry 9.2.1, animal fat)	✓	✓	✓	✓	✓	✓
Whole untreatedinsects (entry 9.16.2 Terrestrial invertebrates, dead)	✗	✗	✗	✗	✓***	✓***
Whole treated insects e.g., freeze dried (entry 9.16.2 Terrestrial invertebrates, dead)	✗	✗	✗	✗	✓***	✓***
Live insects (entry 9.16.1 Terrestrial invertebrates, live)	✗	✓*	✓*	✓*	✓***	✓***
Hydrolysed Insect proteins (entry 9.6.1 Hydrolysed animal proteins)	✓	✓	✓	✓	✓	✓

No restrictions as to the insect species (provided that these are not pathogenic to humans and animals) [pink box]

* If authorized by the National competent Authority of the Member State where the product is being commercialized. [green box]

**Limited to *Acheta domesticus, Alphitobius diaperinus, Bombyx mori, Gryllodes sigillatus, Gryllus assimilis, Hermetia illucens, Musca domestica,* and *Tenebrio molitor*.

*** If authorized by the National competent Authority of the Member State where the product is being commercialized under the specific conditions applicable to the processed pet food.

Fig. 1. List of the admitted insect products for the diet of different animals (reproduced from https://ipiff.org/wp-content/uploads/2019/12/IPIFF-Guide-on-Good-Hygiene-Practices.pdf).

European Union. The European Food Safety Authority (EFSA) assesses the company's documentation, submitted in the 'Novel Food application,' to evaluate potential safety risks associated with the product's consumption. This evaluation forms the basis for the EC's final decision on whether to authorize its commercialization at the EU level.

Since 2021, the following insect products have been allowed by the EU as human food: dried yellow mealworm and frozen migratory locust (2021); frozen and freeze-dried lesser mealworm and partially defatted whole house cricket (2023) (IPIFF 2022). In the EU, insect products are considered Novel Food and the risk assessment process is performed by the European Food Safety Authority (EFSA) (Precup et al. 2022).

An important event was also the first "*Insects to feed the world conference*" which was organized in the Netherlands by Wageningen University and Research (WUR) and the Food and Agriculture Organization (FAO) (van Huis & Vantomme 2014). This first conference was attended by 450 participants from 45 countries. Afterwards follow-up conferences have been organized in China and Canada. Another international conference organized is "Insecta", which from 2015 onwards is organized each year in Germany attracting over 250 participants (ATB 2018).

Currently most insect production in Europe is for the feed sector (van Huis 2020). For human consumption crickets, locusts and mealworms are produced. Left-over substrates are also commercially used to replace mineral fertilizers (Derrien & Grassi 2022). Over the past decade, several EU projects have been undertaken. Notably, the "Enabling the Exploitation of Insects as a Sustainable Source of Protein for Animal Feed and Human Nutrition" (PROTEINSECT) project (€3.9 million; 2013–2016) assessed the potential use of insects as a novel protein source for animal feed (Proteinsect 2013). The "SUStainable INsect CHAIN" (SUSINCHAIN) project (€8.7 million; 2019–2023), involving 35 scientific and industrial partners, investigated the value chain of insects for both food and feed (Susinchain 2019). Additionally, the "Insect Doctors" project (€4.2 million; 2019–2024) aims to train approximately 15 Ph.D. students as insect pathologists to prevent infectious diseases in mass-reared insects (Insect Doctors 2019).

Moreover, research centers have emerged such as the LOEWE-Center for Insect Biotechnology and Bioresources with one of the biggest entomological research program (Vilcinskas 2013). Moreover, international master program such as "Insect Biotechnology and Bioresources" encompassing modules on "insects as food and feed" (Insect Biotechnology & Bioresources 2023) are continuously developed as well as summer school on insects as food and feed at Wageningen University (Wageningen University 2023).

The exact number of business operators in insects as food and feed in Europe is not known, but of the about 80 members of IPIFF two third are business operators. Among stakeholders, major constraints perceived were lack of financial investments and price and demand uncertainties, while legal restrictions were perceived to constrain upscaling opportunities across all supply chain stages (Niyonsaba et al. 2023). To stimulate upscaling, the use of more substrates should be allowed while the range of insect-based ingredients for feed and food products should enlarge.

6.1 Mealworm

The mealworm emerged as the second most important species in insect farming within the EU and was among the first insects that have been approved by the EU food safety administration as a food for humans (Grau et al. 2017). Based on investments into large scale production technologies and a strong patent portfolio, the French Company Ynsect attracted hundreds of millions investment capital to establish the worldwide biggest mealworm farms (de Sousa 2023). The biggest mealworm producer in Germany is Alpha-Protein, also investing in the development of sustainable aquafeed and higher added value products (Röthig et al. 2023). When compared to BSF larvae, the mealworm displays a lesser adaptability to agricultural and industrial side streams as a diet. For example, BSF larvae can detoxify secondary metabolites in agricultural side streams such as gossypol in cotton press cake (Tegtmeier et al. 2021). Even liquid manure can be used as a diet for BSF larvae. The large-scale production of mealworm requires infrastructural and operational safety measures to protect employees from the development of allergies (Siddiqui et al. 2022). On the other hand, mealworm-derived food and feed derived additives are better accepted by the public than maggot derived counterparts (Grau et al. 2017). Mealworms are less resistant to pathogens compared to the larvae of the BSF, whose immune system relies on over fifty antimicrobial peptides. These peptides exhibit a diet-dependent expression pattern in the BSF larvae (Vogel et al. 2018). In Europe, a primary objective is achieving antibiotic-free and sustainable insect production. Ynsect has invested in chip-based strain management to preserve genetic diversity in mealworm strains, preventing inbreeding-based depression and resulting in higher susceptibility to pathogens and stress. Other strategies include the use of immune priming or probiotic bacteria to enhance the insect's resistance (Grau et al. 2017).

6.2 BSF

The economic profile of European industrial BSF operators is very diverse (IPIFF 2022). Approximately 80% of BSF rearing companies are micro-enterprises, which include innovative startups. Most of these companies have invested less than 0.5 million euros. Less than 20% of the companies have made investments up to 5 million euros, and only 6% have invested more than 5 million euros (IPIFF 2022). In the IPIFF platform, there are a total of 19 industrial operators listed as BSF breeders/producers (see Table 1).

Table 1. IPIFF members involved in *Hermetia illucens* production.

Company	Country	Foundation year	References
Agronutris	France	2011	https://www.agronutris.com/en/
BEF Biosystems	Italy	2016	https://www.bef.bio/
Ecofly	Austria	2017	https://www.ecofly.at/en
Enorm	Danemark	2018	https://enormbiofactory.com/
Entogreen	Portugal	2012	https://www.entogreen.com/
Entoprotech	Israel	2016	https://entoprotech.com/
Hermetia	Germany	2006 (1st EU)	http://hermetia.de/
Hexafly	Ireland	2016	https://hexafly.com/
Hipromine	Poland	2015	https://hipromine.com/
Illucens	Germany	2009	https://www.illucens.com/
Innovafeed	France	2016	https://innovafeed.com/en/
Mutatec	France	2015	https://mutatec.com/en/home/
Nasekomo	Bulgaria	2022	https://nasekomo.life/
Next Protein	France	2015	https://nextprotein.co/
Probenda	Germany	2021	https://probenda.de/
Protix	Netherland	2009	https://protix.eu/
Reinartz	Germany	2014	https://www.reinartz.de/en/
Wandepunkt fuz	Germany	2020	https://wendepunkt-fuz.com/

Table 2. Worldwide industries involved in *Hermetia illucens* production not IPIFF members.

Company	Country	Foundation year	References
BioflyTech	Spain	2012	https://bioflytech.com/
Beta Bugs Ltd.	UK	2017	https://www.betabugs.uk/
Entocycle	UK	2017	https://entocycle.com/
La Compagnie des insects	France	2014	https://www.compagniedesinsectes.com/
SFly	France	2015	http://sflyproteins.com/

Other producers of European and non-European countries, who have not joined the IPIFF platform, but are active in BSF production (Table 2).

The commercial landscape of BSF producers is diverse, with some exclusively focusing on rearing, others on transforming it into feed, and only a few engaging in both. Additionally, certain companies provide ready-to-use suspended larvae and/or frozen eggs of BSF as starters for plant rearing globally. These services often include business consultancy and troubleshooting support to help businesses and entrepreneurs establish and operate BSF farms (IPIFF 2022). Refer to Tables 1 and 2 for an overview of key companies involved in various aspects of BSF production, while Table 3 lists those offering technical services to support BSF producers.

A list of the products obtainable from an BSF rearing, with the related characteristics and applications available on the web, is shown in Table 4 (Livin Farm 2023). Other products (pellets, chitin, chitosan, glucosamine or melanin) are known to be potentially available but no information could be found.

It is necessary to point out that, in the EU, the main obstacles in insect-rearing business development are at the normative level (Bosch et al. 2019). In particular, the most relevant EU regulatory restrictions are related to the type of insect rearing substrate. In the EU, insects reared for feed fall under the definition of 'farmed animal' (Article 3.6 of Regulation EC n. 1069/2009), which has several consequences for the choice of the organic resource to be used as substrate. In the EU, for instance, the use of several substrates such as ruminant proteins, catering waste, meat-and-bone meal, and manure are not allowed for any farmed animals (insects comprise) (Regulation (EU) No. 767/2009), in line with regulations on transmissible bovine spongiform encephalopathy. Currently the only authorized rearing substrate for insects, as farmed animals, are:

Table 3. Companies worldwide that provide services and technical assistance to BSF producers.

Service companies	Country	References
Danish Technological Institute	Denmark	https://www.dti.dk/
DIL-EV	Germany	https://www.dil-ev.de/
Inagro	Belgium	https://inagro.be/
Insectengineers	Netherland	https://www.insectengineers.com/
Kinsects	Italy/Senegal	https://www.kinsect.eu/
Livinfarms	Germany	https://www.livinfarms.com/
Matìs	Iceland	https://matis.is/
Phileo-Lesaffre	France	https://phileo-lesaffre.com/en/
Rethink Resource	Switzerland	https://rethink-resource.com/
VDL insect system	Netherland	https://www.vdlinsectsystems.com/en

Table 4. Products obtainable from BSF mass rearing with the related characteristics, applications and prices (Livin Farm 2023).

Type	Characteristics	Applications
De-fatted protein powder	Balanced amino acid profile Very good digestibility > 85% Highly palatable	In **pet food** products, given its nutritional profile and hypoallergenic properties In **fish feed** for high growth performance, a good feed conversion rate, and a good gut health In **shrimp feed** as an attractant for better feed intake In **broiler and pig feed** for better nutrient digestion and productive performances
Fat	High in lauric acid that has antibacterial and antiviral properties An easily digestible source of energy Naturally palatable	In **piglet and dog feed** for improved feed intake and better gut health In **broiler feed** with productive performances
Fertilizer	High organic matter (> 85%) with nitrogen and minerals Contains chitin that improves the defense mechanisms of plants	**Soil amendments** for farms, gardens, horticulture, and greenhouses
Fresh Larvae	Fresh larvae (frozen or alive)	Treats for pets, fish, poultry, or pigs
Dry Larvae	Easily digestible	Pet food snacks Bird and Reptile food
Puree	Easy digestible, source of energy	Canned pet food
Eggs	As starters	

- Animal feed materials according to the EU catalogue of feed materials and authorized as feed for food producing animals (Regulation EU No 68/2013);
- Food produced for human consumption, but which is no longer intended for human consumption for reasons such as expired use-by date or due to problems of manufacturing or packaging defects (excluding meat and fish, thus processed animal proteins (PAPs)) (Former foodstuffs of vegetable origin: Regulation (EU) No 68/2013 Permitted former foodstuffs of Animal origin (non-PAPs) and Regulation (EU) No 142/2011, Annex X, Chapter II, Section 10);
- Other types of organic waste of vegetable nature such as gardening and forest material (Regulation (EC) No 767/2009, Annex III and Regulation (EC) No 68/2013 Directive 2008/98/EC) (Bosch et al. 2019).

Despite the potential unsuitability of manure, faeces, and urine from a sanitary standpoint, certain industrial research centers, such as Entocycle in the UK, breed BSF larvae on pigsties' sludge. These larvae are then utilized to feed pigs, forming a circular economy system (Entocycle 2023). A recent report explores the profitability of producing BSF larvae on pig manure, even though it is currently not legally permitted (Groeneveld et al. 2021). The study indicates that an enterprise can process approximately 900,000 kg/year of wet pig manure with BSF larvae, yielding around 89,000–104,000 kg of live BSF larvae per year. The potential for dried frass production lies between 166,000–170,000 kg per year. The report identifies the high current cost price of live starter larvae as the most critical parameter in the business model (Groeneveld et al. 2021). Additionally, sector operators consider the inability to use domestic or organic wastes a significant legal limitation.

7 Discussion

Insects are still harvested and consumed by many ethnic groups in the world, primarily in tropical zones where they are readily available throughout the year. The recognition of insects as viable food for humans and feed for animals in the Western world has emerged in the last 15 years. The key to making this feasible lies in insect farming. Compared to traditional livestock, producing mini livestock (insects) offers several environmental advantages, including lower greenhouse gas and ammonia emissions, reduced land and water usage, and the ability to rear insects on low-value organic side streams. These benefits have fueled the rapid growth of the insect industry, encompassing both cottage and large-scale industrial production in tropical and temperate zones. However, the swift progress of the sector has outpaced the development of (inter)national legislative frameworks, prompting food safety authorities worldwide to engage in ensuring the safe production and processing of insects. Consequently, in the last five years, several insect products for both food and feed have received approval to enter the market.

The major insect groups reared are three mealworm species (but predominantly *T. molitor*), several cricket species (mainly *A. domesticus*) and locust species (such as *L. migratoria*) as food, and two fly species as feed (primarily *H. illucens*) as feed. In Africa, Asia, and Latin America, several insect species are currently being reared or semi-domesticated. However, in the Western world, the consumption of insects as human food remains a niche market, requiring consumers to adjust to the idea that insects can be a viable food source. Meanwhile, insects as feed are primarily intended for pets, poultry, pigs, and fishes.

The insect industry's overview across different continents reveals distinct patterns. In Australia, North America, and Europe, the primary focus is on insect products for animal feed, particularly Black Soldier Fly (BSF) larvae and mealworms. In Africa, BSF is predominantly utilized in animal feed to replace costly ingredients, with leftovers repurposed as fertilizer. Asia, Latin America, and Australia emphasize insects as food more than Europe or North America. Larger companies, with investments exceeding $100 million, are primarily located in Europe and North America, rearing BSF larvae, crickets, and mealworms. Across all continents, the industry comprises numerous small and medium-sized companies specializing in the same insects. However, in Asia and Latin America, various other insect species are reared or semi-domesticated. In Asia, there are companies focused on waste management using BSF, degrading leftovers from the palm oil industry in Indonesia and Malaysia, or catering waste in China. Cricket farming in East Africa and Thailand operates as a cottage industry. Each continent has professional organizations fostering industry development: AFFIA in Asia, IPAA in Australia, ALPA in Latin America, IPIFF in Europe, and NACIA in North America. Several global projects, such as EU initiatives on the insect value chain and veterinary diseases of insects, along with academia-industry collaborations by CEIF in North America, facilitate research and development worldwide.

The insect industry faces significant challenges across all continents. One major challenge is legislation, with many countries lacking a comprehensive framework. In the EU, IPIFF has played a crucial role in advocating for legislative changes that have allowed insects for fish, poultry, and pig feed, while several insect products are now approved as food. Another challenge is pricing, which remains high in many countries. However, it is anticipated to decrease with the adoption of automation, the utilization of inexpensive side streams, the implementation of green energy practices, and economies of scale. For insects as food, a significant hurdle is consumer reluctance due to feelings of disgust and neophobia. However, as the public becomes better informed about the safety, sustainability, and processing of insect products, acceptance is expected to increase (van Huis & Rumpold 2023). Additionally, the industry may face challenges related to diseases, as evidenced by an outbreak of bacterial disease in cricket rearing in East Africa. Addressing these challenges will be essential for the sustainable growth of the insect industry globally.

Insect rearing differs significantly from established practices in poultry and pig farming, necessitating the development of technologies from the ground up. Many aspects were initially unknown, including the insects' biology, susceptibility to diseases, required abiotic conditions, and suitable cheap organic side streams for rearing without compromising food and feed safety. Additionally, the regulatory framework was lacking, and decisions are still pending on the safety of various organic side streams as breeding substrates. The industry is experiencing rapid development through ongoing research and development efforts. Notably, 90% of all scientific articles on edible insects have been published in the last six years, highlighting the recent surge in knowledge and exploration. The collaboration between academics and industry is expected to propel the insect sector forward swiftly. However, it's essential to acknowledge that failures will be a part of the learning curve in this dynamic and evolving field.

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Manuscript received: September 12, 2023
Revisions requested: October 16, 2023
Revised version received: December 6, 2023
Manuscript accepted: January 10, 2024