CHAPTER

19

Progress and challenges of insects as food and feed

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19.1 Introduction

Insects have been eaten since ancient times and have probably been underestimated as an important food source for early man. This can be deduced from the fact that: (1) insects are eaten by virtually all nonhuman primates; (2) there is archaeological evidence of insectivory by hominids; and (3) insects are an important part of the diet of many traditional societies (van Huis, 2017b). In the first chapter, we will show examples demonstrating that insect species from most insect orders are eaten all over the world. However, this food source is threatened because of overexploitation, habitat destruction, and pollution. Furthermore, if we would like to promote insects as food and feed, the insects need to be farmed as mini-livestock.

As will be reviewed, one of the major advantages of insect production compared to common livestock systems is the lower environmental impact (greenhouse gas and ammonia emissions, less water and land use). Another advantage is that insects can contribute to a circular economy, as some can be reared on organic side streams.

The farming of insects raises challenges: (1) (ento)technology (how to rear insects; can we automate the systems?); (2) which insect species can we rear on what kind of organic side streams; (3) breeding (genetic improvement) has been carried out for decades in livestock systems, but for insects it is very new and promising area, considering their short life cycle; (4) disease management and welfare issues for farmed insects.

We will also discuss the fact that, nutritionally, insects compare very well to traditional meat products and provide possible health benefits. When it comes to marketing, there are many insect products on the market; we will discuss whether consumers are ready to accept this novel food and how we can devise strategies to increase that acceptance.

A main issue is the legislation, as insects have never been on the menu in Western societies. The interest only goes back about 10 years, so the regulatory framework is lagging behind.

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Legislation is largely concerned with food and feed safety, so issues such as allergies and chemical and biological contaminants need to be addressed.

But gradually the societal landscape seems to be changing where the edible insect industry is concerned. It may be a very promising new agricultural sector, and we will outline some future outlooks.

We will start with harvesting from nature and then discuss farming, processing, and marketing.

19.2 Harvesting from nature

More than 2000 species of insects are harvested from nature, and the most eaten species are beetles (order of the Coleoptera) followed by caterpillars (Lepidoptera), wasps, bees and ants (Hymenoptera), grasshoppers and crickets (Orthoptera), true bugs (Hemiptera), termites (Isoptera), dragonflies (Odonota), flies (Diptera), and others (Fig. 19.1). Other arthropod groups, such as spiders and scorpions, are also eaten. They are harvested from all over the world, but most species have been recorded from Mexico, the Democratic Republic of Congo, and South-East Asia (Fig. 19.2). That is not because more species are eaten in those countries compared

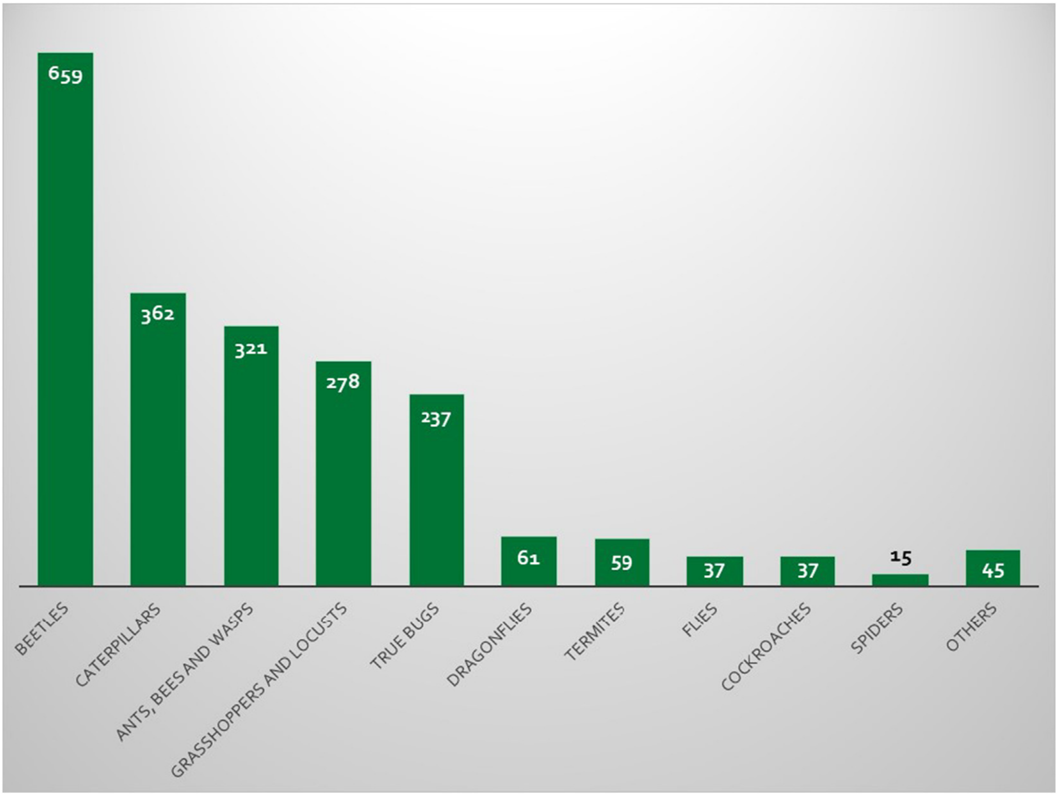

FIGURE 19.1 The number of recorded edible insect species per insect order in the world (Jongema, 2017).

to their neighbors, but rather that there is more research activity. For instance, in Mexico, Julietta Ramos Elorduy wrote an impressive number of articles on edible insects (Pino Moreno, 2016), and in the Democratic Republic of Congo, Malaisse has written several publications, listing a number of edible insect species (Malaisse, 1997).

19.2.1 Coleoptera

Beetles can be eaten as adults but mostly as larvae. One of the most popular edible insects from around the world is the larva of the palm weevil *Rhynchophorus* spp. (Coleoptera: Curculionidae), and a different species is eaten on each continent: in Africa *R. phoenicis*, in Asia, *R. ferrugineus,* and in Latin America *R. palmarum*. They are collected from different palm species, such as the oil palm *Elaeis guineensis*, *Raphia* spp., *Cocos nucifera*, *Metroxylon sagu*, and *Phoenix dactylifera*. Traditional societies have also semidomesticated the species. For example, the South American palm weevil *R. palmarum* is attracted by odors of palm tissue of felled or naturally fallen palms, where they oviposit. For that reason, the Tukano in the north-western Amazon fell trees with the explicit intention of harvesting the larvae a few months later (Dufour, 1987). In Africa, palms are cut down to extract sap, which is used for making palm wine. Later the trunks are revisited to extract the larvae of *R. phoenicis* (Dounias, 2003). The decision to harvest may depend on the sound the larvae make in the trunk, already mentioned by Chesquière (1947). In Cameroon, the larvae are grown in plastic boxes containing fresh palm tissue. This method is less destructive and requires only a quarter of the raffia compared to collection in the wild (Muafor et al., 2017). Also, in Thailand, farming techniques for the palm weevil *R. ferrugineus* have been developed (Hanboonsong et al., 2013). Many

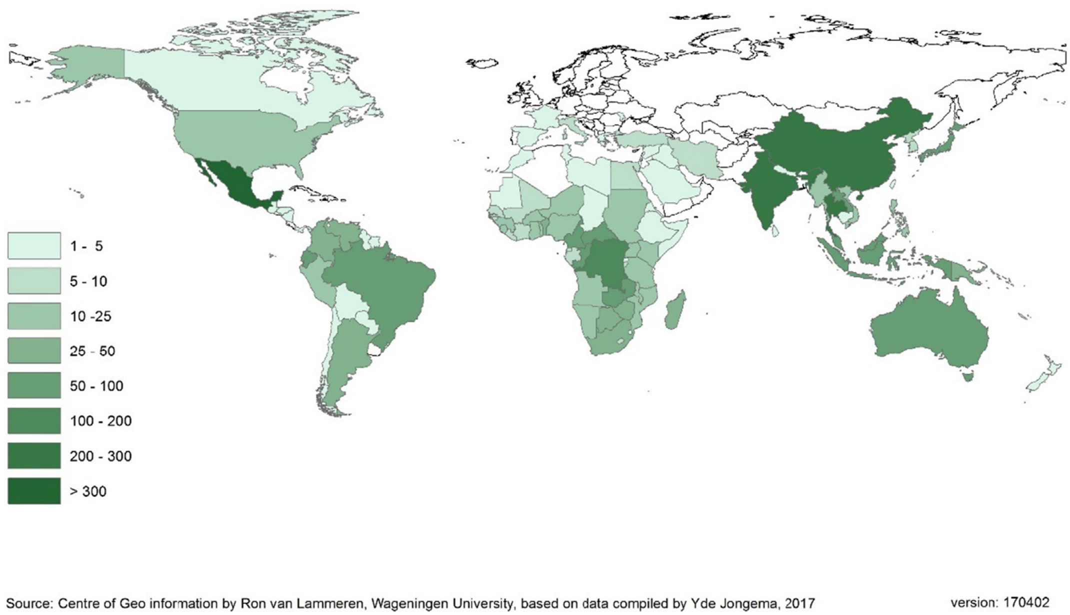

FIGURE 19.2 The number of recorded edible insect species per country (Jongema, 2017).

more beetle species are eaten and an overview of those in sub-Saharan Africa is given by van Huis (2021b).

19.2.2 Lepidoptera

A very large number of caterpillar species are eaten. In central Africa alone, Malaisse et al. (2017) listed close to 100 species. One of the most popular in southern Africa is the mopane caterpillar, *Imbrasia belina* (Lepidoptera: Saturniidae), feeding on the mopane tree *Colophospermum mopane*. However, the insect is so popular that overexploitation has occurred, which is reason enough for promoting sustainable harvesting (Baiyegunhi and Oppong, 2016). Strategies to combat overexploitation include restrictive harvesting periods (Akpalu et al., 2007), maintaining a sufficient number of fifth-instar caterpillars, safeguarding the host tree, and preserving the pupae (Gondo et al., 2010). Attempts to rear the mopane caterpillar have failed mainly because of parasitism, predation, and diseases (Ghazoul, 2006). In West Africa, the shea caterpillar *Cirina butyrospermi* (Lepidoptera: Saturniidae) from the shea tree (*Vitellaria paradoxa*) is eaten because it is very nutritious (Payne, 2019). Pupae of the domesticated silkworm *Bombyx mori* (Lepidoptera: Bombycidae) are eaten in Asia. However, a number of wild silkworm species are also eaten, e.g., the pupae of the wild silkworm, *Borocera cajani* in Madagascar (Lepidoptera: Lasiocampidae) (Wilmet et al., 2013, pp. 55–67), and *Anaphe* spp. (Lepidoptera: Notodontidae) in Africa (Banjo et al., 2006). The bamboo caterpillar, *Omphisa fuscidentalis* (Lepidoptera: Crambidae) is eaten in the north of Thailand. Traditionally they were collected by cutting down entire bamboo clumps. However, a method has been developed in which a hole is cut in the specific infested internode to obtain the larvae without sacrificing the whole plant.

19.2.3 Hymenoptera

Concerning the Hymenoptera (ants, bees, and wasps), the weaver ant *Oecophylla smaragdina* (Hym.: Formicidae) is very popular food in Southeast Asia (Van Itterbeeck et al., 2014). The seasonally available large larvae and pupae are collected by piercing the nest with a bamboo stick, such that the contents fall into the bag/basket hanging close to the top of the stick. Ant species such as the red wood ant *Formica polyctena* (Hymenoptera: Formicidae) have been used for their gland secretions with interesting smells and flavors (e.g., pine, coriander, cinnamon, peach, vanilla), which can be used as aroma in order to create new and innovative dishes (Evans et al., 2017). Bee brood is often used as food in many countries (Ghosh et al., 2020). From the honeybee, *Apis mellifera* (Hymenoptera: Apidae) late pupae and adult drones can be useful for human consumption. Removing drone broods from the hive to control Varroa mite infections is a common practice. The unused drone brood is very nutritious and can be used as human food, such as in the cookbook by Ambühl (2017), or as animal feed (Ghosh et al., 2020).

19.2.4 Orthoptera

Locusts are grasshoppers (Orthoptera: Acrididae) but differ in that they can change their behavior. Locusts are normally solitarious (like grasshoppers), but in crowded conditions they become gregarious (different morphology, color, and behavior) and can swarm. Most locust species are consumed when an upsurge or plague occurs, such as is the case with the desert locust, *Schistocerca gregaria*, the red locust (*Nomadacris septemfasciata*), the brown locust (*Locustana pardalina*), the migratory locust (*Locusta migratoria*) in Africa, and *Schistocerca cancellata* in Latin America (van Huis, 2020). Many grasshopper species are eaten, e.g., in India (Haldar and Malakar, 2017), sub-Saharan Africa (van Huis, 2003), and Madagascar (Van Itterbeeck et al., 2019). Although they are often pests, mechanical control (hand collecting) has the advantage that excellent food can be harvested without the use of pesticides, as is the case with the grasshopper *Sphenarium purpurascens* (Orthoptera: Pyrgomorphidae), a pest of crops such as maize and beans in Mexico (Cerritos and Cano-Santana, 2008). The variegated grasshopper *Zonocerus variegatus* (Orthoptera: Pyrgomorphidae) is a pest of numerous food and cash crops (e.g., banana, cassava, cowpea, maize) in central and West Africa, but despite its unpleasant odor (called "criquet puant" in French, i.e., stinking locust), it is a popular food in Nigeria (Idowu et al., 2004; Kekeunou et al., 2006). A very common food item in East Africa is the edible grasshopper *Ruspolia differens* (Orthoptera: Tettigoniidae), which can be seasonally harvested during their nocturnal flight from street lights by women and children in Uganda, or commercially using huge light traps that lure them in drums through funnels of corrugated iron sheets (Mmari et al., 2017).

19.2.5 Hemiptera

Concerning the Hemiptera, in Mexico, they eat the edible eggs collected from reed bundles, purposely put in the lakes, and call it "Mexican caviar" (Bachstez and Aragon, 1945). Giant water bugs, in particular *Lethocerus indicus* (Hemiptera: Belostomatidae), which grows up to 12 cm, are an expensive delicacy in many parts of Asia; their odor provides a flavor profile that is essential for consumer acceptance of food products such as chili pastes or fish sauces (Tao and Li, 2018). The stinkbug *Encosternum delegorguei* (Hemiptera: Tessaratomidae) is consumed as a delicacy in South Africa and Zimbabwe. To remove its defense chemical, which stains the skin and affects vision, a laborious method can be employed, which removes the heads and stink glands, or a more efficient method in which multiple stinkbugs can be processed at once by pouring hot water over them (Dzerefos et al., 2013).

19.2.6 Isoptera

Termites (Isoptera) are a popular food all over the world. In most cases, people eat the future kings and queens, which swarm out of the nest after the first rains following the dry season. The most common collection method is to put a light source above a receptacle filled with water. They fly to the light and fall in the water, to be scooped out later. They lose their wings in the process. Termites are highly nutritious with high levels of protein, fats, key vitamins, and minerals (Fombong and Kinyuru, 2018). The soldiers are also eaten (Paoletti et al., 2003). In Africa, the most common way to collect them is to break a part of the termite mound and then insert a grass stem or reeds from the river into the hole in the mound. The soldiers will bite into the stem after which they will be stripped into a container of water (van Huis, 2017a). They are sometimes pounded into cake. For use as feed for chickens, farmers break small termite nests (Isoptera: *Microtermes* spp.) or parts of termite mounds (van Huis, 2017a).

19.2.7 Diptera

From the Diptera order, the insects reared as feed for animals are the common housefly, *Musca domestica* (Diptera: Muscidae) and the black soldier fly *Hermetia illucens* (Diptera: Stratiomyidae) (van Huis et al., 2020). However, other dipteran species available for (artificial) rearing are blow flies (Calliphoridae) and flesh flies (Sarcophagidae).

19.2.8 Other insect groups

From the Ephemeroptera (mayflies) order, the lake fly *Caenis kungu* (Ephemeroptera: Caenidae) is collected by swirling baskets in the clouds of flies coming onto the shores of Lake Victoria; these are then eaten as dried cakes (Williams and Williams, 2017; Ayieko and Nyambuga, 2009). Mayflies of the genus *Povilla* (Ephemeroptera: Polymitarcyidae) are dried and made into "insect flour" for meal preparation (Bergeron et al., 1988). In Yunnan China, dragonfly larvae are eaten, the most common ones being *Crocothemis servilia* (Odonota: Libellulidae), *Gomphus cuneatus* (Odonata: Gomphidae), and *Lestes praemorsus* (Odonata: Lestidae) (Feng et al., 2001). Pemberton (1995) reports the consumption of larvae of the large dragonfly (Odonata: Libellulidae) species (*Crocothemis* sp. and *Neurothemis* sp.) from Balinese rice fields in Indonesia.

19.2.9 Other arthropods

Costa-Neto and Grabowski (2021) give an overview of the consumption of arachnids (spiders, scorpions, mites, and ticks) and myriapods (millipedes and centipedes) either as food or medicine all over the world. There is a well-known custom of eating tarantulas in Cambodia (Münke et al., 2014). These large ground-dwelling species are mainly consumed as a side dish with rice in rural areas, but are also served in restaurants as an appetizer. The popular published viewpoint is that tarantula was consumed to combat starvation during the Khmer Rouge era. However, it may have a much longer history. The species *Haplopelma* spp. (Araneae: Theraphosidae) are reported to be eaten in Borneo, Cambodia, China, Myanmar, Thailand, Malaysia, Singapore, and Vietnam. Also, in South America, people consume large spiders such as *Theraphosa* spp. (Araneae: Theraphosidae) that live in terrestrial burrows (Costa-Neto and Grabowski, 2021). Meyer-Rochow (2005) mentions the consumption of two spider species by the Ao Nagas from Nagaland in North-east India: the semicolonial spider *Avansa* sp. semicolonial spider and the giant orb-weaver *Nephila clavata* (Araneae: Nephilidae).

19.3 Farming insects

19.3.1 General

Harvesting from nature is one option. However, if we would like to promote insects as either food or feed, they need to be reared. That has been done by traditional societies to a certain extent, and we call this semidomestication; examples have been given above and more are given by Van Itterbeeck and van Huis (2012).

The last 10 years have witnessed an increasing interest all over the world to rear insects as food or feed. This sudden global interest was partly triggered by the FAO publication "Edible insects: future prospects for food and feed security" (van Huis et al., 2013), which assured global legitimacy, while academic validity was guaranteed by an associated university (Vantomme, 2017). Publications on edible insects had appeared previously, e.g., the one by Meyer-Rochow (1976), but they failed to trigger much interest. The reason for this is that during the last decades, there has been an increased awareness that the land available for livestock is too constrained to satisfy future demand and that the environmental impact of producing conventional production animals is too high. Insects grown as mini-livestock score better on both points. To demonstrate the scope of academic interest, using the words "edible insects" in the Web of Science scores 900 hits from 1945 to 2020. From 2015 onward, there was a steep increase in the number of publications (Fig. 19.3), constituting 91% of the total.

There is also an increased interest from private enterprise as shown by the number of *entopreneurs*, which is more than 310 worldwide (latest update March 27, 2022) (BugBurger, 2021).

The edible insects concerned are: (1) three mealworm species (Coleoptera: Tenebrionidae): the yellow mealworm (*Tenebrio molitor*), the lesser mealworm (*Alphitobius diaperinus*), and the superworm (*Zophobas morio*); (2) several cricket species, e.g., from the family Gryllidae (Orthoptera): the house cricket *Acheta domesticus* and the banded cricket (*Gryllodes sigillatus*); and (3) several locust species such as the migratory locust (*L. migratoria*) and the desert locust (*S. gregaria*). Two fly species are mainly used as feed: (1) the black soldier fly *Hermetia illucens*

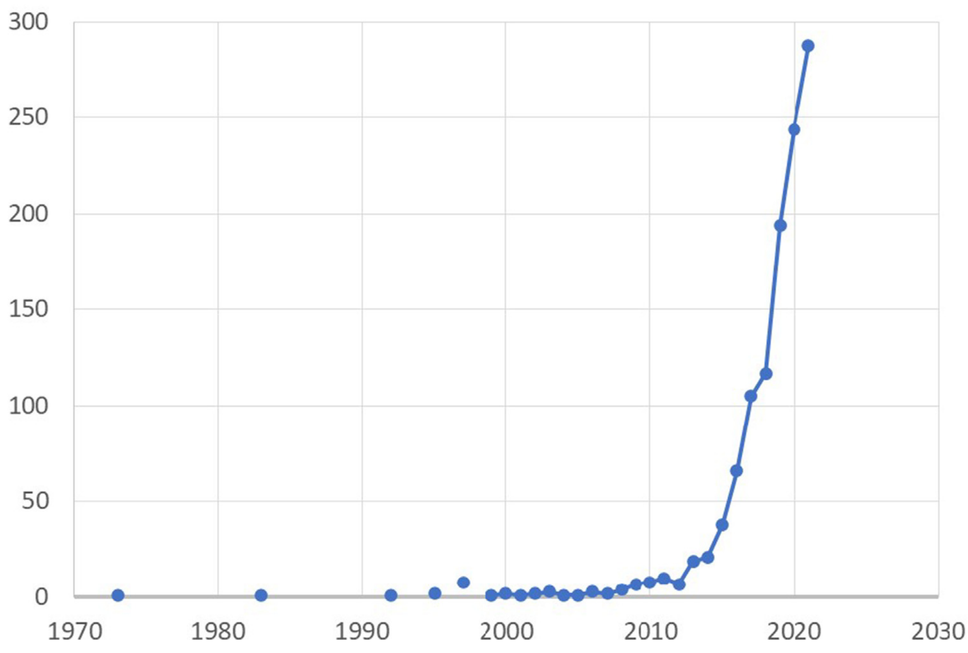

FIGURE 19.3 The number of hits when using the words "edible insects" (from 1945 to 1973 there are no hits) in Web of Science (accessed May 23, 2022).

(Diptera: Stratiomyidae) and the housefly *Musca domestica* (Diptera: Muscidae). With regard to mealworms and crickets, this was partly based on companies who had experience in rearing insects for pets.

19.3.2 Entotechnology

In order to rear insects, an insect production facility must be set up, involving engineering design, construction, and plant operation. There are also many questions to be addressed: for example, what is the effect of feed composition and temperature of the cooling air, etc., on system productivity, conversion efficiency, and energy requirements. And whether to use dry or semidry feeds, what type of larval rearing, reactor configuration, and operational approach. All these issues are discussed in a series of articles (Kok, 2021a,b,c,d).

19.3.3 Genetics

A new area being explored recently is that of genetic improvement (e.g., can we select strains fit for specific waste streams?), where much progress can be expected due to the short life cycle of insects. In China, the Chinese oak silkworm, *Antheraea pernyi* (Lepidoptera: Saturniidae), has been artificially reared since 1651 (Li et al., 2021). The yield of the cocoons and pupae of this insect is now approximately 80,000 tons per year. "Qinghuang_1" is an improved strain (high yield, stability, strong resistance, and broad adaptability) that was obtained using a systematic selection method in 1954. For the domesticated silkworm, *B. mori*, pupae of two strains differed in nutritional content (e.g., carotenoid content) when grown on different diets (Chieco et al., 2019). With crickets there are many viruses and whether commercially reared crickets differ from wild populations in susceptibility to these viruses is worth investigating (de Miranda et al., 2021). In the yellow mealworm *T. molitor*, a selection over 8 years produced larger pupae but a lower survival rate than the ancestral strain (Morales-Ramos et al., 2019). The black soldier fly is now widely used for biotransformation and companies are interested to know if they can select strains that can handle different type of substrates. Strains and their ability to convert different manure types have been investigated (Zhou et al., 2013), and wild strains are also being investigated as a substitute for fishmeal in aquafeeds (Ghughuskar et al., 2020). For the housefly *M. domestica*, different strains have also been investigated with regard to size, egg production, and developmental time (Pastor et al., 2014).

19.3.4 Disease management

The fear of most insect-rearing companies is that a disease will wipe out their colonies. This happened in the United States with the densovirus of the house cricket *A. domesticus* (Weissman et al., 2012). There are many viruses of the crickets as shown by Eilenberg et al. (2017). However, with insects we can switch to rearing other species if necessary, such as the banded cricket *G. sigillatus*, which is less vulnerable to the densovirus then the house cricket. However, the main disease management strategy is to follow strict hygienic rules (Eilenberg et al., 2015).

19.3.5 Insect welfare

When farmed as mini-livestock, the question is raised as to whether they are "sentient beings," which can be researched by looking at their brain, behavior, and communicative abilities. Ethics relates to the question of whether they are just there for our benefit or whether we consider them as coanimals? To discuss the consequences of welfare issues for the industry sector that produces insects for food and feed, van Huis (2021a) uses Brambell's five freedoms as a framework. The central question in this debate is whether insects are "sentient beings." This may be the case, considering: (1) the very efficient functional way in which their brains are organized; (2) their capacity for social and associative learning; and (3) their diverse ways of communication. It has been argued that people should refrain from eating insects because of the sheer number involved (e.g., one pig compared to thousands of crickets) (Knutsson, 2016). However, recommendations to adopt a plant-based diet will inevitably involve the killing of billions of insects (Fischer, 2019). When insects are farmed and killed, the precautionary principle is used; this assumes that they can experience pain. The following is required: (1) establishing guidelines or standards of care in the industry for the well-being and slaughter of farmed invertebrates; (2) more research efforts in the cognitive and emotional capacity of invertebrate species.

19.4 Environment

When harvesting from nature, there are several environmental concerns (van Huis and Oonincx, 2017): (1) habitat changes (logging, bush fires) that may threaten caterpillar species; (2) water pollution that may threaten edible aquatic insects (Williams et al., 2021); (3) pesticide use for edible insect pests (van Huis, 2020); and (4) overexploitation. However, in this chapter we will deal mainly with the environmental impact of farming insects either for food or feed. This can be divided into two parts: (1) the effect on global warming and on water and land use; (2) the insects as converters of organic side streams that contribute to a circular economy.

19.4.1 Greenhouse gas emissions, ammonia, water, and land use

Compared to traditional production animals, the advantages relate to fewer greenhouse gas and ammonia emissions and lower requirements for land and water (Table 19.1).

The edible portion of crickets in Table 19.1 was estimated at 80% (Nakagaki and deFoliart, 1991), but this value depends on the stage of harvesting and could therefore be 100%. The most significant statistic in this table was land use, which is about 10 times less than beef. This land use is mainly related to the use of the feed and can be improved if it were possible to use vegetable or fruit remains or even weeds (Aji et al., 2016; Choo et al., 2017; Ng'ang'a et al., 2020) as feed substrate.

19.4.2 Organic side streams

Whether organic side streams can be used to feed the insects depends on the species chosen. For human consumption, it concerns mainly mealworms and crickets, while for feed

TABLE 19.1 Edible portion, feed conversion efficiency (FCE), and life cycle analysis (LCA) of GHG emissions (CO_2 equivalents), water, and land use of insects and conventional meat.

	Insect[a]	Poultry	Pig	Beef	References
Edible portion (%)	80	55	55	40	van Huis (2013)
FCE (kg feed/kg edible weight)	2.1	4.5	9.1	2.5	van Huis (2013)
GHG emissions (LCA) (CO_2-eq)	14	19	27	88	Oonincx and de Boer (2012)
Water use (LCA) (L/g protein)	23	34	57	112	Miglietta et al. (2015)
Land use (LCA) (m^2/kg protein)	18	47	55	201	Oonincx and de Boer (2012)

[a]*Edible portion and FCE for crickets and the rest for the mealworm* T. molitor.

these are mealworms and flies. One may wonder at the benefit of using insects as feed since it requires an extra conversion cycle. This can be explained as follows: instead of humans eating the insects directly, there is an intermediate step of first feeding the insects to animals, which in turn are eaten by humans. This can only be profitable if: (1) the insects can be fed on low value and cheap organic side streams; (2) there would be additional benefits such as health effects. The requirements for using low-value cheap organic side streams are: (1) They should be reliably available in large quantities; (2) They should be more or less of constant quality; (3) The insects should be able to perform well on these side streams. There does not necessarily need to be just one type of side stream, it can also be a mixture. The major challenge is to find (a mix of) cheap, constant-quality organic side streams available in large quantities on which the insects perform well.

One problem with cheap side streams is that they are often composed of cellulose and lignin and low in protein and the insects do not perform very well on them. Can we use organisms able to digest cellulose/lignin and synthesize it into protein? Several beetles, some cockroaches, and most termites can do much of this, aided by bacteria and protozoa living symbiotically in their guts (Slaytor, 1992). And although termites are difficult to rear, cockroaches can be used as both food (de Oliveira et al., 2017) and feed (Ukoroije and Bawo, 2020).

During the consumption of decaying organic matter, the larvae interact with microorganisms such as bacteria and fungi originating from the substrate, the insect, and the environment. Therefore, the combination of microorganisms and insects needs to be fully researched, e.g., some microbial symbionts of arthropod guts are able to synthesize protein de novo from atmospheric nitrogen (Bar-Shmuel et al., 2020). Or can we treat organic side streams in such a way that they become suitable for insects? Zhang et al. (2021) give an overview of how microbes help black soldier fly, house fly, the waxworm *Plodia interpunctella* (Lepidoptera: Pyralidae), and yellow mealworm to convert organic waste. Some gut microbiota and their secreted enzymes degrade protein, fat, polysaccharide, cellulose, polystyrene, and polyethylene and may inhibit pathogens in organic wastes to make substrates more fit for insects. Schreven et al. (2021), working with chicken manure, recommended that black soldier fly producers should focus on the manipulation of substrate-associated microorganisms as this may increase larval biomass. Over time, the larvae, having a flexible digestive system, may alter the substrate bacterial community composition by inhibiting certain bacteria while dispersing gut bacteria into the substrate (Gold et al., 2018).

One cheap side stream widely available is straw. Would it be possible to ferment the straw first before giving it as a substrate to the insects? The black soldier fly can deal with many organic side streams. Gao et al. (2019) fermented maize straw with *Aspergillus oryzae*. Compared to the control (wheat bran), the larval stage was longer, adult longevity shorter, and fecundity lower. But the pretreatment method improved the bioconversion of maize straw. Qi et al. (2019) used maize and wheat straw diets, fermented by *Trichoderma viride* and *Saccharomyces cerevisiae*, as diets for the house fly *M. domestica*. Straw bioconversion was enhanced, and the larvae could be used as feed for poultry and fish. It has even been investigated whether waste from the insect industry can be transformed using the black soldier fly (Jucker et al., 2020). The black soldier fly can consume different organic materials, reducing the waste volume, obtaining a nutrient-rich animal feed for monogastric animals (pets, poultry, fish, and pigs), fat for processing into high-quality biodiesel, the waste residue as organic fertilizer, and different bio-based products; see for an overview Surendra et al. (2020).

19.5 Nutrition

A review on the nutrient composition of about 236 insect species showed a lot of variation (Rumpold and Schlüter, 2013). This is because there are more than 2000 species of insects that are consumed. However, there are other factors that influence nutritional content during rearing, in particular the diet time of harvesting and gender (Finke and Oonincx, 2014), but also rearing conditions (temperature, humidity, and light regime), processing, and conservation, and even the method of analysis used. Concerning the light regime, Oonincx et al. (2018) showed that insects can synthesize vitamin D de novo. Low irradiance UVb tended to increase vitamin D3 levels in house crickets, vitamin D2 levels in black soldier fly larvae, and vitamin D2 and D3 in yellow mealworms. The suboptimal n-6/n-3 fatty acid ratios of insects can be mediated by supplementing their diet with flaxseed oil, which consists primarily (about 60%) of alpha-linolenic acid (Oonincx et al., 2020). A 4% addition to the diet increased the n-3 fatty acid content 10−20 fold in house crickets, lesser mealworms and black soldier flies, significantly decreasing n-6/n-3 ratios.

Many edible insects provide satisfactory amounts of energy and protein, meet amino acid requirements for humans, are high in monounsaturated and/or polyunsaturated fatty acids, and rich in several micronutrients such as copper, iron, magnesium, manganese, phosphorous, selenium, and zinc as well as riboflavin, pantothenic acid, biotin, and in some cases, folic acid (Rumpold and Schlüter, 2013). When comparing commonly consumed meats (beef, pork, and chicken) with six commercially available insect species for energy and 12 relevant nutrients, the Ofcom model showed that insects were not healthier than meat products; however, when using the Nutrient Value Score, crickets, palm weevil larvae, and mealworm larvae were healthier than beef and chicken (Payne et al., 2016). It showed that insects were not less healthy than meat.

The amino acid spectra of insects generally meet the requirements for human nutrition (Osimani et al., 2017), but the content of essential amino acids differs both within and between insect species. Using mealworms, protein content remained stable in diets that differed two- to threefold in protein content, whereas dietary fat did influence larval fat content and fatty acid profile (van Broekhoven et al., 2015).

19.6 Health benefits

19.6.1 Humans

Stull et al. (2018) attracted a lot of attention with her publication reporting that the consumption of powder of the cricket *G. sigillatus* increased the gut probiotic bacterium, *Bifidobacterium animalis*, almost sixfold. It was suggested that the stimulation was caused by the chitin in the insect supplement. There was also a lot of interest in the publication by Di Mattia et al. (2019), who studied the antioxidant effects of 12 edible insects in vitro. Water-soluble extracts of the grasshopper *Calliptamus italicus* (Orthoptera: Acrididae), the silkworm *B. mori*, and the house cricket *A. domesticus* have two to three times the antioxidant capacity of orange juice or olive oil (both modulate the antioxidant network in humans). Similar results on antioxidant capacity were achieved for the weaver ant *O. smaragdina* (Alagappan et al., 2021), *Gryllus assimilis* (de Matos et al., 2021), and others (Zielińska et al., 2017; Botella-Martínez et al., 2020; Mohsin et al., 2020).

The most common nutrient deficiency in the world is iron deficiency, affecting more than 30% of the global population, an estimated 2 billion people; it is most prevalent in preschool children (47%) and pregnant women (42%) (Bailey et al., 2015). According to the same publication, it is estimated that 17% of the global population has inadequate zinc intake, with the highest estimates in Africa (24%) and Asia (19%); pregnant females and their young children are the highest-risk groups for zinc deficiency overall. According to Mwangi et al. (2018), the levels of Fe and Zn present in 11 edible insect species that are mass-reared and six species that are collected from nature are similar to or higher than in other animal-based food sources. Latunde-Dada et al. (2016) compared in vitro iron availability from insects and sirloin beef. They found that grasshopper, cricket, and mealworms contain significantly higher chemically available Ca, Cu, Mg, Mn, and Zn than sirloin, but the lesser mealworm and sirloin exhibited higher iron bioavailability comparable to that of $FeSO_4$. However, the addition of crickets to refined maize porridge reduced fractional iron absorption from the meal (Melse-Boonstra et al., 2019). Cereals have low iron and zinc bioavailability because of high phytic acid (PA) and phenolic compounds (PC). Affordable and sustainable food-based strategies are crucial in alleviating mineral deficiencies. Gabaza et al. (2018) enriched fermented cereals with mopane worm; the result was an increase in iron and zinc levels, but bioaccessibility was reduced. Bauserman et al. (2015b) made a cereal from locally available caterpillars and concluded that it has appropriate macro- and micronutrient contents for complementary feeding and is acceptable to mothers and infants in the Democratic Republic of Congo. The caterpillar cereal did not reduce the prevalence of stunting at 18 months of age (Bauserman et al., 2015a). However, infants who consumed caterpillar cereal had higher Hb concentrations and fewer were anemic, suggesting that caterpillar cereal might have some beneficial effect.

Angiotensin-converting enzyme (ACE) inhibitors inhibit vasoconstriction and prevent blood pressure from rising. In vitro studies have shown that insects belonging to the

Coleoptera, Diptera, Hymenoptera, Lepidoptera, and Orthoptera orders are a potential source of ACE inhibitors (Cito et al., 2017). However, the in vivo effectiveness of most of these bioactive peptides still must be confirmed (van Huis et al., 2021). Insect protein and possible bioactive compounds have received attention for their possible impact on lipid metabolism. Insect meal from the yellow mealworm exerted pronounced lipid-lowering effects in hyperlipidemic rats, and it was not clear whether this was the result of the chitin or protein of the insect (Gessner et al., 2019). Further studies on hyperlipidemia and fat reduction in humans are necessary. Diabetes mellitus type II is one of the most prevalent diseases in the world, and the yellow mealworm is an adequate source of antidiabetic bioactive peptides inhibiting α-glucosidase (Rivero-Pino et al., 2020).

19.6.2 Animals

Soybean meal and fishmeal are commonly used as a conventional protein source in animal feed. Fishmeal and fish oil are still considered the most nutritious and most digestible ingredients for farmed fish feeds, but due to supply and price variation, their use in compound feeds for aquaculture has decreased (FAO, 2018, p. 51). Also, the sustainability of fishmeal and fish oil has been questioned (Tacon et al., 2009). Soybean meal as an alternative seems to reduce both performance and fish health (Gasco et al., 2018). Therefore, there is interest in using insects in animal feed. This is because from a nutritional perspective insects can fully substitute soybean meal or fishmeal in aquaculture and livestock feed (Gasco et al., 2021). The authors reviewed 129 articles dealing with the effects of insects and their bioactive compounds on the immune system, gut health, microbiota, and resistance to diseases of fish, crustaceans, poultry, pigs, and rabbits. They concluded that the bioactive compounds in insects (chitin, antimicrobial peptides, specific fatty acids) have immune-stimulating, antimicrobial, and/or antiinflammatory properties. So, insects as ingredients in feed not only sustain animal health but also increase resistance to disease.

19.6.3 Plants

Even plants seem to benefit from the leftover substrates of insect rearing. They appear not only to stimulate plant growth but also to protect the plant (Poveda et al., 2019; Houben et al., 2020). Overall, frass tends to have similar or better results when compared to inorganic fertilizers, reducing the prevalence of disease and pathogens. In addition, chitin found in frass also has beneficial properties for plant/crop growth and disease resistance (Chavez and Uchanski, 2021).

19.7 Insect products

There are many different insect products on the market. Below is only a sample of the literature available. For protein bars, crickets are often used (Adámek et al., 2018). Sausages have been prepared with mealworm and crickets (Kim et al., 2016; Keto et al., 2018; Scholliers et al., 2020). An interesting development is to use edible insects for staple foods such as bread

(Bawa et al., 2020; Khuenpet et al., 2020) and pastas (Duda et al., 2019; Carcea, 2020), usually mealworms and crickets. Biscuits can also be fortified with insects, using, for example, palm weevil (Ayensu et al., 2019), silkworm pupae and locusts (Akande et al., 2020), and crickets for schoolchildren in Kenya (Homann et al., 2017).

If the insects are not used for food or feed but other applications, there are more opportunities to use organic waste streams. The fat content of the black soldier fly is high (from 9% to 28% dry matter) and the percentage of lauric acid in the fatty acids is 23%–51%, depending on the rearing substrate of the larvae (Barragan-Fonseca et al., 2017). That is why the insects are used to make biodiesel; among the many publications, see Surendra et al. (2016). The fatty acid profile resembles that of palm kernel and coconut oil. Therefore, black soldier fly fats may turn out to have similar applications to these plant-derived oils, such as glycine-acyl surfactants (Verheyen et al., 2020). The protein of the black soldier fly can be used as a promising base for bioplastics for agricultural purposes (Barbi et al., 2019). The fats of migratory locust and the house cricket are rich in C16 and C18 fatty acids, which makes them suitable for skin care in cosmetics (Verheyen et al., 2018). Chitin from the exoskeleton of insects and chitosan (its deacetylated form) have many practical applications in therapeutic and biomedical products (Morin-Crini et al., 2019).

19.8 Processing

The processing of insects has been described by Rumpold et al. (2017) and Ojha et al. (2021), and an overview of the technology used is reviewed by Sinderman et al. (2021). One of the first steps in processing is decontamination, which is necessary to inactivate pathogens and spoilage microorganisms. This can be done by thermal processes or radiation. The next step is drying by convection, contact, or radiation. As such, the whole larvae can be dried and sold as feed and food. Another option is comminution (grinding or milling). These processes are rather simple, but the disadvantage is the high fat content, which makes the transportation and storage more difficult. Instead of producing the whole larvae or a powder as product, another possibility is the extraction of protein, lipids, and chitin for which several techniques are available. One of the problems associated with processing mealworm is the enzymatic browning. It seems that processing steps such as blanching and high-pressure processing techniques reduce browning, but additional measures such as applying air-tight packaging may be necessary to prevent oxidation (Tonneijck-Srpová et al., 2019). Processing is concerned with delivering products that are safe and of high quality.

19.9 Consumer attitudes

Insect products have been on the market for almost a decade and have received quite a lot of media coverage. However, they are still not mainstream in terms of sales and presence in supermarkets and the makers are still quite small companies (Reverberi, 2021). Consumer reluctance to eat insects has been attributed to psychological and emotional factors such as food neophobia (the fear of unfamiliar foods) and the erroneous association of edible insects with pathogens (Fukano and Soga, 2021). According to Baker et al. (2018) and Russell and Knott (2021), psychological and emotional factors are a very critical barrier to edible insect acceptance. There are many studies on consumer attitudes, which are reviewed among others by: Hartmann and Siegrist (2017), Mancini et al. (2019), Motoki et al. (2021), and Sogari et al. (2019). Consumers are influenced by several factors, such as the following attributes: (1) sensory (e.g., taste, smell, appearance); (2) cognitive (e.g., nutritional value, environmental benefits); and (3) individual traits (e.g., gender, food neophobia, sensation-seeking) (Motoki et al., 2021). Although the cognitive factors may be appealing to consumers (nutritional value, health benefits, and sustainability), consumers may be blocked by strong emotional insect aversions such as disgust and risk perception. Apparently, human curiosity is the biggest deciding factor for the willingness to try insects, which is why (Wassmann et al., 2021) believe that food sensation and innovation seekers are the first adopter of insects as food. Quite a few strategies have been proposed to convince consumers (van Huis, 2019), such as: (1) disguising the insect in familiar products; (2) stressing deliciousness; (3) attractive packaging; (4) making them available in supermarkets; (5) providing information about nutritional value, sustainability, food safety, and health; (6) stressing the proximity between crustaceans and insects; (7) giving people a taste experience, such as bug buffets; (8) using role models such as political figures, film stars, or cooks; (9) cookbooks; and (10) targeting children as they are not yet biased.

19.10 Food and feed safety and legislation

Food safety issues relate to allergies and chemical and biological contaminants. Immunoglobulin-E (IgE)-mediated food allergy is an adverse reaction of the immune system to specific proteins in foods that are usually harmless. In people who have a food allergy, reactions may be caused by crustaceans. Since insects are taxonomically very close to crustaceans (Pennisi, 2015), people that are allergic to crustaceans may also be allergic to insects, an effect known as cross-reactivity (IgE antibodies originally raised against one allergen bind to another structurally related allergen). Besides crustaceans, house dust mites may also cause cross-reactivity. The allergens identified in insects are tropomyosin and arginine kinase. Specific treatments (enzymatic hydrolysis combined with thermal treatments) could eliminate IgE-reactivity of edible insects (Ribeiro et al., 2021). Insect-rearing workers and consumers with allergic diseases (in particular, food allergy to crustaceans) are the major risk groups.

There are many chemical contaminants involved, often derived from the substrate on which the insects are reared. These contaminants are heavy metals, dioxins and polychlorinated biphenyls, polyaromatic hydrocarbons, pesticides, veterinary drugs, mycotoxins, and plant toxins (Meyer et al., 2021). Several studies have shown that the heavy metals, copper, lead, mercury, chromium, and cadmium can accumulate in the black soldier fly (Wu et al., 2020; Elechi et al., 2021) and arsenic in mealworms (van der Fels-Klerx et al., 2016). Mycotoxins (van Broekhoven et al., 2014) and veterinary drugs (Lalander et al., 2016) can be degraded by insects, but not much is known about the resulting metabolites. It is even possible to use mealworms to safely obtain protein from mycotoxin-contaminated grain

(Ochoa-Sanabria, 2019). The same principle was applied by Attiogbe et al. (2019) to compost mercury-containing organic waste using the black soldier fly. As the black soldier fly accumulates mercury, the compost could be safely used after this bioremediation.

Concerning biological contaminants, the top three of the bacterial pathogens associated with insects for food are *Staphylococcus aureus*, pathogenic *Clostridium* spp., and pathogenic species of the *Bacillus cereus* group, while for insects as feed, the last group seems also to be a major risk (Vandeweyer et al., 2021). Application of a heat treatment is sufficient to eliminate spores of *Bacillus* spp. (Vandeweyer et al., 2018). Concerning viruses, there seems to be a low risk for the three viruses investigated (Vandeweyer et al., 2020). Research has been conducted on whether edible insects could be a transmission vector of the novel zoonotic coronavirus SARS; however, the risk seems to be extremely low (Dicke et al., 2020). Although prions in principle could enter insects reared on contaminated substrates, this is unlikely with strict substrate quality control.

There follows an overview of the possibilities to feed insect proteins to certain animal species according to EU rules (Fig. 19.4). More than 20 applications have been submitted to the EU for the authorization of insects as a novel food, such as the house cricket, the lesser mealworm, the banded cricket, *Hermetia illucens* (black soldier fly), *Locusta migratoria* (migratory locust), and *Apis mellifera* male pupae (honeybee drone brood) (IPIFF, 2022a). Following the opinions of the European Food Safety Authority (EFSA), the following insect products as human food have been authorized by the EU in 2021 and 2022: frozen, dried, and powder

Feed stocks	Regulatory approval
Vegetal substrates	✓
Former food stuff: vegetal, dairy[1] & eggs[1]	✓
Former food stuff: meat & fish	✗
Catering waste & slaughterhouse products	✗
Animal manure	✗

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Insect production

According to IPIFF members the most commonly used insect species in animal feed are the black soldier fly, the yellow mealworm and the common housefly larvae

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Target species	Protein	Fat	Live larvae[2]	Whole insects (dried or frozen, not milled)
Pets	✓	✓	✓	✓
Fish	✓	✓	✓	✗
Poultry	✓	✓	✓	✗
Swine	✓	✓	✓	✗

FIGURE 19.4 Possibilities to feed insect products to certain animal species according to EU rules. Insect proteins as aquafeed allowed since July 1, 2017 and as feed for poultry and swine since the seventh of September 2021. *Modified from: https://ipiff.org/insects-eu-legislation/; for further details: IPIFF (2022b; p. 21 and 25).*

1. Authorised only in case the eggs have been cooked/the milk pasteurised.
2. Live larvae are permitted under national legislation in certain EU Member states.

FIGURE 19.5 Four main factors influence the pace of growth of the insect industry. *Modified after De Jong and Nikolik (2021). Rabobank*

yellow mealworm; dried and frozen migratory locust; and dried, ground, and frozen house cricket. An authorization of partially defatted house cricket is expected in 2022 (IPIFF, 2022a). It is expected that more and more insect species will be allowed to enter the market.

19.11 Conclusions/future trends

A major challenge for the industry is to lower the cost price of production. This can be done by automating the production process and by finding cheap organic side streams on which the insects thrive well.

According to a Rabobank report, the market for insect protein in 2021 is 10,000 metric tons, but by 2030, it is expected to reach half a million metric tons, of which 40% would be in aquaculture (De Jong and Nikolik, 2021). According to this report, the growth would be explained by sustainability aspects and functional benefits such as palatability and health. The limits to growth are high costs and prices, the current limited production capacity, and legislation. The 500,000 metric tons predicted by 2030 is expected to be a turning point for the insect industry. Efficiency gains will result in decreasing costs. The pace of acceleration to double or quadruple from then on would depend on R&D, legislation changes, capital investment in the sector, and marketing (see Fig. 19.5).

Insect protein as a pet food ingredient is currently the largest market and will probably remain one of the largest, reaching 150,000 metric tons globally by 2030. Several factors support growth in this area, including the high protein content, sustainability, and hypoallergenic features. In 2020 and 2021, at least two large pet food companies incorporated insects into their products (Woolfson, 2021; Nestle, 2020).

Meticulous Research (2021) estimates that the compound annual growth rate of the value of the edible insects' market is expected to increase by 26.5% to reach $4.63 billion by 2027, while in terms of volume, it is predicted to increase by 28.5% to reach 1400 metric tons by 2027. The growth in the edible insect market is mainly driven by factors such as rising greenhouse gas emissions from livestock and poultry, high nutritional value of insects, low environmental impact over their entire life cycle, and low risk of transmitting zoonotic diseases. However, the nonstandardized regulatory framework, psychological and ethical barriers to insects as food, and allergies due to insect consumption are expected to restrain the growth of this market to a certain extent.

Due to the newness of the edible insect industry, legislation is lagging behind, but this obstacle is expected to be resolved. The potential of insects as a new sustainable food and feed source is receiving increasing recognition. The sector of insects as food and feed is developing fast and organizations are being formed to embed the industry in a more conducive environment. However, the sector can only progress if the insect industry, the academic world, governmental organizations, and the public cooperate closely.

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