Food and Agriculture
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LOOKING AT EDIBLE INSECTS FROM A FOOD SAFETY PERSPECTIVE

Challenges and opportunities for the sector

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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Cover photographs: clockwise from bottom right: Cricket powder, roasted mealworms, and fried silkworm pupae. ©Yerai Ibarria.
Design and layout: Tomaso Lezzi

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PREFACE

While the subject of edible insects inherently encompasses a vast array of topics, from insect ecology to various rearing practices and processing methods, the primary objective of this publication is to provide an overview of the potential food safety issues associated with the production and consumption of insects. The farming of insects for food and feed is relatively recent and brings with it both benefits and challenges, some of which this publication explores. The regulatory frameworks that govern edible insects in various regions are discussed. In addition, the document highlights some of the other challenges, such as research gaps and scaling up production, that the insect sector will need to overcome if it is to have a more global reach. The intended audiences for this publication are food safety professionals, policymakers, researchers, insect producers, as well as consumers.

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Cookies (above) made from cricket flour (below).

ABBREVIATIONS AND ACRONYMS

ACFS	Agricultural Commodity and Food Standards
ACNF	Advisory Committee on Novel Foods
AMR	antimicrobial resistance
CFIA	Canadian Food inspection Agency
EC	European Commission
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization of the United Nations
FDA	Food and Drug Administration (USA)
FD&C Act	Federal Food, Drug, and Cosmetic Act (USA)
FSANZ	Food Standards Australia New Zealand
GHG	greenhouse gas
GRAS	Generally Recognized As Safe
HBCD	hexabromocyclododecane
IPIFF	International Platform of Insects for Food and Feed
KEBS	Kenya Bureau of Standards
LCA	life cycle assessment
LOQ	limit of quantification
MOH	mineral oil hydrocarbons
OECD	Organisation for Economic Co-operation and Development
PAH	polyaromatic hydrocarbons
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzodioxins
PCDF	polychlorinated dibenzofurans
PDCAAS	protein digestibility-corrected amino acid score
PMTDI	provisional maximum tolerable daily intake
SDG	Sustainable Development Goals
WHO	World Health Organization

Belelang goreng or fried grasshoppers from Indonesia.

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Hormigas culonas (*Atta laevigata*) is a popular delicacy in Colombia.

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EXECUTIVE SUMMARY

The release of the pioneering FAO publication, *Edible insects. Future prospects for food and feed security* in 2013 spurred considerable interest in insect farming. While insects have been part of the normal diets of many cultures in various regions through the centuries, the practice is not widespread in the Western world. However, with growing concerns about the environmental effects of food production, sustainable agriculture is garnering increasing support within our food systems. This has led to an increased interest in using insects as an additional source of nutrition in human food and animal feed, propelling research activities as well as business opportunities worldwide.

Until recently edible insects have been collected mainly from the wild but farming insects for human as well as animal consumption is now on the rise. Their high fecundity, high feed conversion efficiency, and rapid growth rates make insects viable and attractive candidates for farming. In addition, they can be reared in small, modular spaces, making it feasible to raise them in rural as well as urban farm settings. The low carbon, water and ecological footprints associated with insect production, as compared to those of other livestock species, make them attractive from an environmental sustainability standpoint. In general, edible insects are a good source of protein, fatty acids, vitamins, and minerals, though the nutritional profile is insect species dependent. This makes them a potential food source for healthy human diets. Insects can also be a nutritionally beneficial and sustainable source of feed for animals. These factors make insects a good prospect to help address food insecurity issues related to a rising global population, without simultaneously harming the environment.

However, the benefits of this emerging food source must be weighed against all possible challenges: for instance, any food safety issues that could pose health threats to consumers. As with other foods, edible insects can also be associated with a number of food safety hazards. This publication covers some of the major food safety hazards that should be considered, including biological agents (bacterial, viral, fungal, parasitic) as well as chemical contaminants (pesticides, toxic metals, flame retardants). Safe and successful insect production must include efforts to prevent, detect, identify and mitigate such food safety concerns. Food safety risks can be higher when insects are harvested from the wild and consumed raw. Farming insects under controlled hygienic conditions and implementing sanitary processing techniques should reduce some hazards, such as microbiological contamination.

An important area of food safety consideration is the quality and safety of the feed or substrates used for rearing insects. The use of raw materials that are alternative to conventional feed are being explored as potential substrates for mass production of insects. Some of these raw materials include food side streams such as food waste, agricultural by-products or manure from livestock farms. The high nutritional content and low cost of such side streams provide a means to enforce circular economy in the process, in addition to further reducing the environmental footprint and economic costs associated with insect farming. However, as the nutrient content and food safety aspects of reared insects depend on the substrate, further studies and monitoring will be needed to determine the quality and safety of such side streams as well as the insects that are produced.

Insects and crustaceans (shrimp, prawns, etc.) belong to the arthropod family. While allergic reactions to shellfish are well-known, the potential allergenic risks associated with consuming edible insects needs further investigation. Individuals already allergic to crustaceans are particularly vulnerable to developing allergic reactions to edible insects, due to allergen cross-reactivity. The immune systems of shellfish-allergic individuals are sensitized to certain proteins from crustaceans. Recognition of similar proteins in insects upon consumption can trigger the immune system to initiate an allergic reaction. In addition to cross-reactivity, there is also a risk associated with developing *de-novo* sensitization to yet unidentified allergens from insects. Research in this area must be broadened to gain a better understanding of this risk.

Other challenges facing this emerging sector are also discussed in the publication. These include the general absence of insect-specific regulations governing the production and trade of insects as food and feed, issues related to upscaling the production of insects, and overcoming the negative attitude associated with insect consumption among some consumers.

Consumer purchases fried insects in a market in Cambodia.

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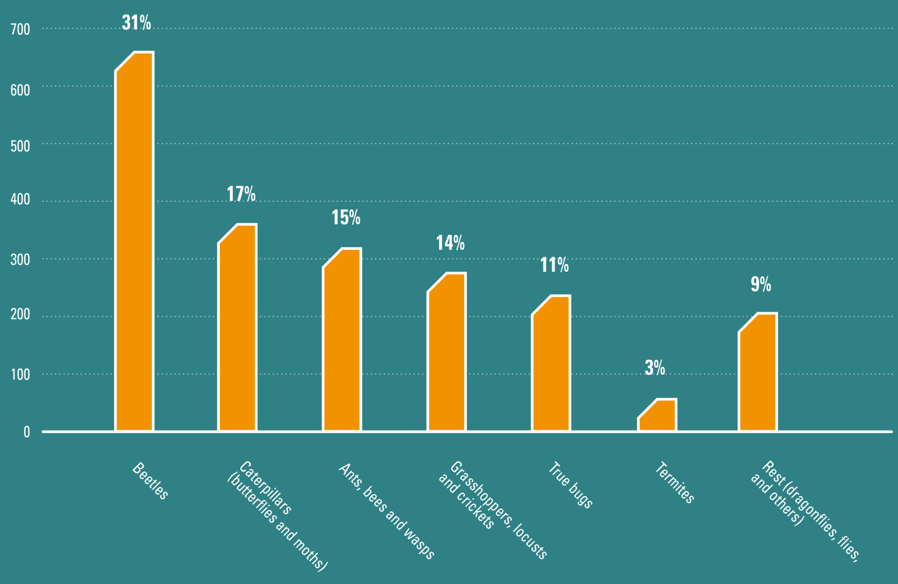
INTRODUCTION

Historically, many cultures in different parts of the world have made insects a part of their diets (Meyer-Rochow, 1975). The earliest recorded accounts of people eating insects date to the eighth century BCE in the Middle East (Bodenheimer, 1951). According to recent estimates, approximately 2 111 species of insects are consumed in about 140 countries (Jongema, 2017), with entomophagy documented around the world: in Asia and Australia and in Africa and the Americas (van Huis, 2003; Ramos-Elorduy, 2009; Yen, 2015; Costa-Neto, 2016; Kim *et al.*, 2019; Raheem *et al.*, 2019). While some of the common insect species consumed worldwide (**Figure 1**) are known, there is currently insufficient data to estimate the quantity of the insects that are consumed.

According to Jongema (2017), 92 percent of known edible insect species are wild-harvested, 6 percent are semi-domesticated, and 2 percent are farmed. Among the known wild-harvested edible insect species 88 percent are terrestrial in origin and the remaining collected from aquatic ecosystems (Yen, 2015). There are a few exceptions involving

FIGURE 1. **NUMBER OF RECORDED EDIBLE INSECT SPECIES PER GROUP IN THE WORLD**



Source:
Adapted from Jongema 2017.

insects that are bred mainly for the purposes of obtaining products that are of commercial value, like silk and honey (FAO, 2013; Jongema, 2017). Recently, there are some other insect species that have been farmed intensively; for instance, the industrialized production of house crickets (*Acheta domesticus*) in the United States of America mainly for use in pet food and as fishing bait (Morales-Ramos *et al.*, 2020).

With the global population expected to reach 9.7 billion by 2050 (UN, 2019), concerns are growing over whether the planet's finite resources such as agricultural land and freshwater can meet the food needs of so many people. Such food security concerns are propelling exploration into various alternative food sources for humans (insects, fungi, cultured meat, micro and macro algae) and feed for animals (insects, food side streams, biofuel by-products) that are nutritionally sound and can be obtained sustainably (Parodi *et al.*, 2018; FAO and WHO, 2019). Insects are fast emerging as a viable food and feed group with mass production gaining some popularity globally. This can be attributed to the significant nutritional value of insects as well as environmental benefits and improvements in livelihoods associated with insect farming (FAO, 2013; Dobermann, Swift and Field, 2017).

BENEFITS OF EDIBLE INSECTS AND INSECT FARMING

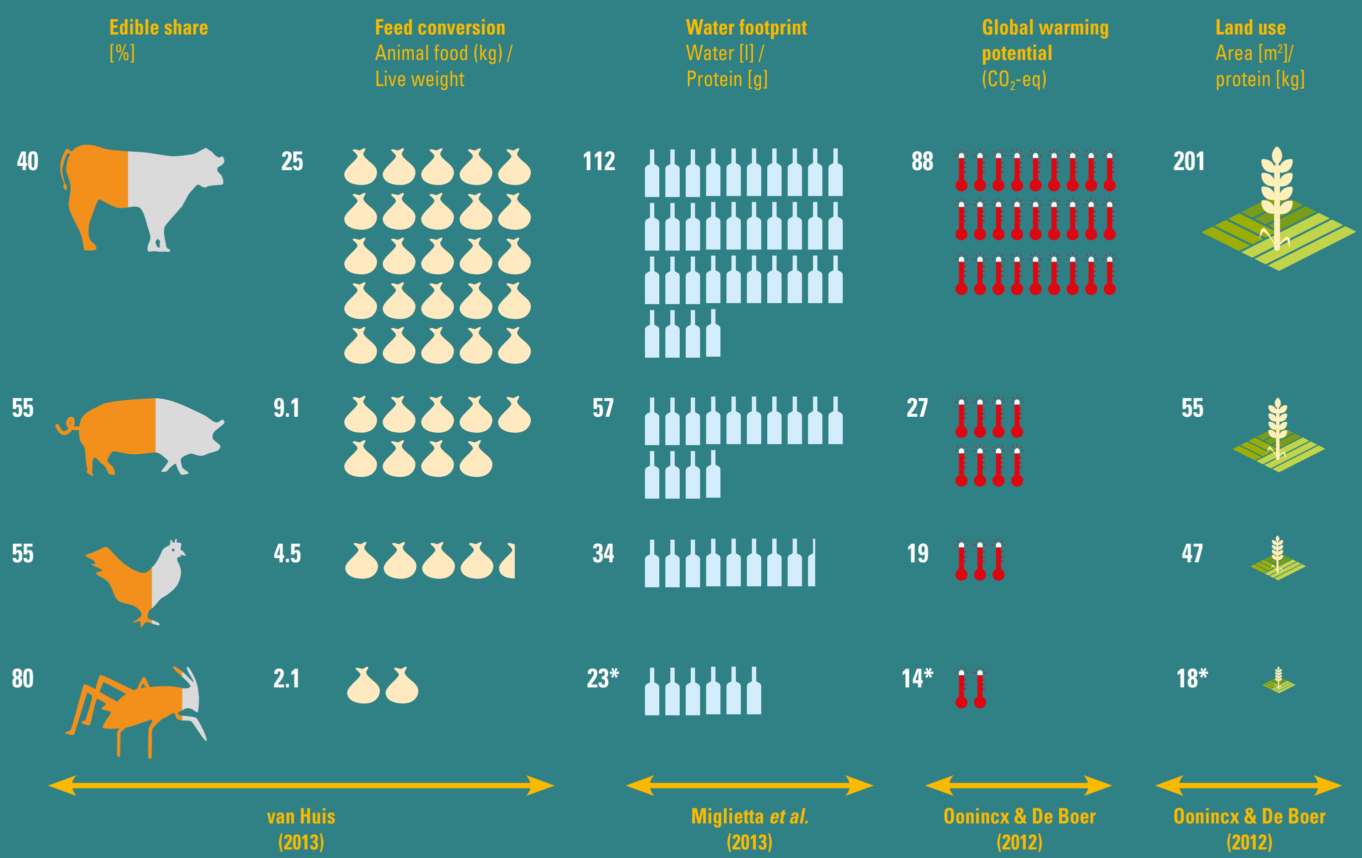
ENVIRONMENT

There are several environmental benefits (**Figure 2**) associated with insect farming (Dobermann, Swift and Field, 2017), farming mealworms requires less water than farming conventional livestock (Miglietta *et al.*, 2015). Farmed insects can satisfy their water needs from their feed or substrates. In addition, certain edible insect species, like mealworms, are more drought resistant than cattle (FAO, 2013; van Huis, 2013). Most of the water needs for insect farming is related to processing steps such as cleaning.

Production of edible insects has a high land-use efficiency when compared to traditional protein sources (Alexander *et al.*, 2017). In fact, it takes two to ten times less agricultural land to produce one kg of edible insect protein compared to one kg of protein from pigs or cattle (Oonincx and de Boer, 2012).

The production of greenhouse gas (GHG) emissions by insects is far lower than that of conventional livestock (Oonincx *et al.*, 2010). For instance, pigs produce 10 to 100 times more GHG per kg of weight than mealworms (FAO, 2013).

FIGURE 2. **COMPARISON OF FEED CONVERSION, WATER, GLOBAL WARMING POTENTIAL, AND LAND NEEDED TO PRODUCE 1 KG OF THE LIVE ANIMAL. ALSO SHOWN IS THE PERCENTAGE OF EACH ANIMAL THAT IS EDIBLE.**



** denote numbers are for mealworms, not crickets.*

Source:
Personal communication with Dr van Huis.

Life cycle assessment (LCA)[1] shows that in the case of the yellow mealworm (*Tenebrio molitor*) and the superworm (*Zophobas morio*), land-use and GHG emissions are lower than for pigs, poultry, and cattle, per kg of protein (Oonincx and de Boer, 2012; van Huis and Oonincx, 2017). This aspect contributes to climate action under the Sustainable Development Goal[2] 13 (SDG 13) (Dicke, 2018).

According to Oonincx and de Boer (2012), while less energy is required to produce one kg of edible protein from insects than beef, it is comparable with pork and requires slightly more energy than chickens. The energy use in insect production is mainly due to maintaining climate-controlled facilities for the poikilothermic[3] insects (Oonincx and de Boer, 2012). However, Oonincx and de Boer (2012) also found that larger larvae in mealworms produce surplus metabolic heat, which they suggested could be used for rearing the smaller and more heat-demanding larvae. In addition to rearing, processing steps for insects like drying can also be energy intensive, as was found through a life cycle analysis of black soldier flies by Salomone *et al.* (2017).

Other reasons to consider insects as a sustainable source of protein include the fact that they can be reared all year around, most of their body is edible, they have high fecundity and growth rates, and they efficiently convert their substrates into body mass. Nakagaki and DeFoliart (1991) estimated that up to 80 percent of a cricket's body is edible as compared to 55 percent of a chicken and a pig, and 40 percent of a cow (**Figure 2**). In fact, studies state that crickets are twice as

[1] LCA methodology typically measures the environmental impact of a product through the entire supply chain.

[2] Sustainable Development Goals, https://www.un.org/sustainabledevelopment/sustainable-development-goals. (Accessed 1 March 2021).

[3] Organisms with body temperatures that fluctuate with the ambient temperature of the environment are poikilothermic.

efficient as poultry in converting feed to protein, and they are four times and twelve times as efficient as pigs and cattle, respectively (Imathiu, 2020). In addition, insects can be farmed in quite small spaces making them versatile in terms of farming settings, whether rural or urban.

NUTRITIONAL ASPECTS

Rumpold and Schlüter (2013) published the nutritional composition of 236 edible insects and found that they are rich in protein (dry matter), dietary fibre and beneficial fatty acids. The insects were also found to be good sources of micronutrients like iron, zinc, magnesium, manganese, phosphorus, selenium and zinc. However, at present there is insufficient information as to the bioavailability of these micronutrients. The vitamin content in edible insects includes riboflavin, pantothenic acid, biotin and, in some cases, folic acid (Rumpold and Schlüter, 2013).

The nutritional composition among different edible insect species is highly diverse. Various factors like the quality of their substrates, the developmental stage of harvesting, and environmental factors can all affect the nutrient content of edible insects (Finke and Oonincx, 2014; Payne *et al.*, 2016). Apart from nutritional content, the quality of nutrients present in insects is also an important consideration. Oibiokpa *et al.* (2018) analyzed the protein quality of four edible insects in Nigeria – field cricket (*Gryllus assimilis*), grasshopper (*Melanoplus foedus*), termite (*Macrotermes nigeriensis*) and moth caterpillar (*Cirina forda*). While all four insect species were found to have high protein content, crickets were determined to have a higher protein quality and digestibility (measured as protein digestibility-corrected amino acid score or PDCAAS[4]) as compared to the others (Oibiokpa *et al.*, 2018).

[4] PDCAAS provides an assessment of how well the dietary protein intake matches the body's requirement for amino acids (FAO and WHO, 1991).

To facilitate a more comprehensive compilation of the nutrient intake estimations from edible insects for humans, the nutrient content (on a fresh weight basis) of the yellow mealworm (*T. molitor*) was deposited in the FAO/INFOODS Food Composition Database for Biodiversity (BioFoodComp2.1) (Charrondière *et al.*, 2013; FAO/INFOODS, 2013; Nowak *et al.*, 2016).

FOOD SECURITY

A lot of attention is being paid to the potential of edible insects for diversifying diets and improving food security in many parts of the world, especially where there is food scarcity (FAO, 2013; van Huis, 2015; Tao and Li, 2018). Land-use efficiency is important for achieving food security for a growing population (Foley *et al.*, 2015; FAO and OECD, 2018). In this regard, insects are a better alternative to traditional sources of proteins (as explained above). The nutritional composition of insects combined with the more efficient use of natural resources and a lower environmental footprint all contribute to SDG 2 (zero hunger), SDG 3 (good health and well-being) and SDG 12 (responsible consumption and production) (Dicke, 2018).

Food waste,[5] agricultural residues and agri-business processing byproducts are being considered as a sustainable source of substrates for farmed insects. Insect-based bioconversion of such side streams is gaining attention as studies have shown that a number of edible insect species can convert low-value side stream materials into high-value commodities like biomass (proteins, lipids), biofuels, lubricants and frass[6] (used as fertilizer) (Ramos-Elorduy *et al.*, 2002; Roffeis *et al.*,

[5] Food waste can include “materials that remain after, or are produced during, the processing, manufacture, preparation or sale of human food. This can include former food products, such as edible material intended for human consumption, arising at any point in the food supply chain, such as that collected from restaurants, retail, or from household food scraps” (FAO, 2019).

[6] Frass is the biological waste or excrement of insects. It also contains undigested food and metabolic excretions (Gullan and Cranston, 2014).

2015; van Broekhoven *et al.*, 2015; van Zanten *et al.*, 2015; Surendra *et al.*, 2016; Salomone *et al.*, 2017; Pleissner and Rumpold, 2018; Fowles and Nansen, 2020; Ites *et al.*, 2020; Surendra *et al.*, 2020). Around 931 million tonnes of food, or 17 percent of the total food available to consumers, was wasted in 2019 (UNEP, 2021). Therefore, this avenue represents an attractive way to reuse food waste, and contribute to a circular economy (SDG 12). Several private enterprises in different regions of the world are already employing this method and are looking to expand the application (Fowles and Nansen, 2020).

ECONOMIC

Selling edible insects that have either been gathered from the wild or farmed offers opportunities for livelihood diversification to rural communities, especially in areas where entomophagy is already practised (Kozanayi and Frost, 2002; Imathiu, 2020). Insects have higher fecundity rates than conventional livestock, allowing farmers to harvest them multiple times a year and, therefore, increase their economic benefits. Findings by Halloran, Roos and Hanboonsong (2017b) and Hanboonsong, Jamjanya and Durst (2013) show that in Thailand, cricket farming has improved the lives of many farmers in rural parts of the country with more than 20 000 such farms established earning over USD 3 million a year. Cricket farming has also enabled women to develop entrepreneurial skills, thereby improving the quality of life in rural communities (Halloran *et al.*, 2017a). In southern Africa, larvae of the moth *Imbrasia belina* (mopane worms), which is mainly harvested from the wild, are consumed for their nutritional value by rural and to some extent, urban populations. The worms are also traded in markets providing a good source of income to the rural communities

A variety of edible insects sold in a market in Thailand.

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(Makhado *et al.*, 2014). Sustainable harvesting practices (**Box 1**) must be put in place for edible insects that are collected from the wild to prevent overexploitation (Thomas, 2013). Moreover, changing climatic conditions threaten this important source of food and income. For instance, in Botswana a prolonged dry spell resulted in a shortage of mopane worms in 2019, which affected rural livelihoods (Dube, 2020; Tebele, 2020).

In the European Union, the expansion of the insect farming sector is expected to increase the number of jobs from a few hundred to a few thousand by 2025, thereby contributing to the economy (Derrien and Boccuni, 2018; IPIFF, 2020). The primary production and processing of edible insects is predicted to be associated with these job increases. Employment opportunities are also linked to jobs created to support the sector, such as specialized retail, administration, logistics and research (IPIFF, 2020). In addition, growing interest in the insect-based animal feed sector (currently allowed in aquaculture and pet food) may also lead to more jobs.

INSECT FARMING – APPROACHES AND APPLICATIONS

There are several factors that determine the viability of an insect species for mass production. The insect species must be fast-growing in easy-to-maintain environmental conditions, can feed on substrates that are abundant and cheap, they must be able to tolerate high densities without cannibalism, among other characteristics (Schneider ed., 2009). Insect farms today range from small-scale farms where the insects are grown with minimal investment in infrastructure and that produce a few tonnes per year to large-scale farms that use automation and produce thousands of tonnes per year.

Farmed or wild-harvested insects are mainly used for animal feed (livestock, poultry, aquaculture, pets), human food, waste management, and frass as fertilizer. These applications and the regulatory provisions that drive them vary among countries. Beyond these applications, insects in nature provide important ecological functions, such as pollination, seed dispersal, carbon sequestration in soils, pest control, among many others (Dangles and Casas, 2019). However, an analysis of such applications is beyond the scope of this publication.

BOX 1. WILD-COLLECTED INSECTS – SUSTAINABLE HARVESTING PRACTICES NEEDED TO PREVENT OVEREXPLOITATION

While loss of habitat remains one of the major causes for declining insect populations, a greater push for entomophagy may lead to overexploiting insects from their natural habitats, as has happened with *witjuti* and *bardi grubs* and honey ants in Australia, mopane caterpillars in Zimbabwe and several insect species in Mexico (Ramos-Elorduy, 2006; Yen, 2009; FAO, 2013; van Huis and Oonincx, 2017).

Overexploitation of insects will threaten the biodiversity and the stability of the ecosystem in the area if checks are not put in place through regulations and enforcement. Such measures will also safeguard rural livelihoods. Sustainable harvesting protocols and guidelines for habitat conservation along with easing barriers for insect farming and trading will be needed to prevent over-harvesting of insect species of interest from the wild. In some communities, restrictive harvest period policies have been implemented by traditional leaders to prevent overharvesting of edible insects, for instance, sustainable harvesting of mopane worms in the Uukwaluudhi Conservancy in Namibia (FAO, 2007). In countries where insects are collected from the wild, it is also important to enforce appropriate policies that control the misuse and/or overuse of agro-chemicals to minimize food safety risks associated with chemical hazards (DeFoliart, 1999).

Beneficial insect populations are in decline in many parts of the world due to climate change, declining habitats and overuse of pesticides (Hallman *et al.*, 2017; Lister and Garcia, 2018; van Strien *et al.*, 2019; Seibold *et al.*, 2019; Cardoso *et al.*, 2020). While not all edible insect species are threatened, the practice of gathering edible wild insects can help to draw attention to the importance of other insects and their habitats, thereby promoting biodiversity conservation (DeFoliart, 1997; Yen, 2009).

INSECTS AS ANIMAL FEED

Rising prices and sustainability aspects for soybean and fishmeal, two principal protein sources for animal feed, are some of the factors spurring an interest in alternative sources of protein for animals. Insects can be an attractive source for high-protein animal feed (van Huis, 2013). Studies have reported that insect meal, fish meal and soybean meal are quite similar in their amino acid profiles (Barroso *et al.*, 2014; Pinotti *et al.*, 2019). Moreover, the environmental footprint associated with the production and trade of raw materials that go into conventional animal feed is much higher than for insects, which can be a local, sustainable, and an on-demand product (van Huis and Oonincx, 2017). However, from an economic point of view, insect-based feed can be more expensive than conventional feed (Arru *et al.*, 2019). Various studies provide different perspectives on this (Joly and Nikiema, 2019; Pinotti *et al.*, 2019; van Huis, 2020). According to PROteINSECT (2016), the value of dipteran (black soldier fly and house fly larvae) insect meal is at least twice that of soybean, but less than fishmeal. Pinotti *et al.* (2019) reported that the prices for insect-based feedstuff might be even higher for lesser mealworm (*Alphitobius diaperinus*) and black soldier fly (*Hermetia illucens*) costing six and nine times respectively more per unit of protein than feed derived from soybean. However, as production volumes increase and the feed production chain undergoes greater optimization, the cost price of insect meal is expected to drop (All about feed, 2016).

Globally the market for insects as feed was valued at USD 688 million in 2018 and is expected to reach USD 1.4 billion by 2024. The aquaculture sector accounted for more than 50 percent of the global insect feed market in 2018 (Globe Newswire, 2020). The growing demand for fish

Using insects for animal feed is a growing area.

and the need to find sustainable alternatives to the use of fishmeal as feed make insects an attractive choice. Revenue is also expected to be generated by using insects in the poultry sector (Globe Newswire, 2020). Insects can also be found in pet food in some countries. Some of the more promising insect species to find application in animal feed, due to ease of commercial large-scale production and meeting suitable dietary requirements, are black soldier flies and yellow mealworms (Veldkamp and Bosch, 2015; Ipema *et al.*, 2020a,b).

INSECTS AS FOOD FOR HUMAN CONSUMPTION

The consumption of insects in the tropical and sub-tropical regions have been extensively studied (van Huis, 2016). Representatives from various insect groups (**Figure 1**) are consumed in these regions. Insect-eating habits are not only associated with nutritional aspects but also closely related to socio-cultural practices and religious beliefs in the region. Edible insects are also used to complement diets when other protein sources are not available during certain times of the year. In some regions, certain insect species are even considered as delicacies (van Huis, 2016).

While insects have never been considered as a food source in Western countries, for today's consumers who looking for nutrient-rich and ecologically sustainable sources for food, edible insects can be a perfect candidate (Klein, 2019; Owoeye, 2020). However, in order to gain deeper inroads, insect producers need to overcome the deep-rooted aversion to insects that is prevalent among Western consumers.

The global market for edible insects is expected to reach approximately USD 8 billion by 2030 (Globe Newswire, 2019). As of 2017, crickets (house

Fresh grasshoppers collected from the wild and on display at a local market in Niger.

cricket and field cricket) occupy the largest share in the global edible insect market. The other categories include mealworms (super worm, yellow mealworm, lesser mealworm), grasshoppers, ants and silkworms.

WASTE MANAGEMENT BY INSECTS

Studies show that certain insect species can be used to recycle low-quality plant-derived side streams and animal excreta (manure) into high value biomass (Ramos-Elorduy *et al.*, 2002; Broekhoven *et al.*, 2015; Miech *et al.*, 2016; Gold *et al.*, 2018; Xiao *et al.*, 2018; Zhang *et al.*, 2019). This bio-conversion not only provides a low-cost source of substrates for insects, but it is also an attractive opportunity to create resources that find applications in animal feed, biofuels, pharmaceuticals and crop fertilizers. Recycling food waste generated in urban and peri-urban settings by using insects like black soldier fly to generate protein sources for animal feed has been discussed by Law and Wein (2018). However, it is important to note that the nutritional content as well as microbiological and toxicological profiles of insects that are produced depend on the composition of the side streams used as substrates (Harsányi *et al.*, 2020; Parry, Pieterse and Weldon, 2020)

Yellow mealworms and superworms can also degrade materials like styrofoam and other forms of polystyrene as well as polyethylene (Yang *et al.*, 2015a and 2015b; Nukmal *et al.*, 2018; Brandon *et al.*, 2018; Koh *et al.*, 2020). More research is needed to show the safety aspects of using insects for animal feed or even for frass (fertilizer) after rearing them on diverse waste materials.

INSECT FRASS AS FERTILIZER

One of the potential benefits of insect farming is that the frass it generates can be used to improve soil fertility. Based on the nutrient composition and increase in soil biological activity, Houben *et al.* (2020) proposed that frass from yellow mealworm larvae (*T. molitor*) may be a sustainable source of fertilizer. However, the impact of rearing substrates on the quality of frass needs more research. For instance, Alattar, Alattar and Popa (2016) suggested that untreated solid residues by black soldier flies, grown on food waste, has a stunting effect on maize plants.

In addition, contaminants in substrates can be excreted and may end up in the soil when frass is applied as a fertilizer. This is especially true under circumstances where insects are raised for waste management and their frass is collected for use in agriculture. More research is needed to ensure that no food safety hazards are inadvertently introduced into the food supply this way.

OTHER APPLICATIONS

The applications for insect farming also include producing biofuel, as well as chitin and lipids, which have uses in food, textiles, cosmetics, pharmaceuticals and as surfactants (Gortari and Hours, 2013; Houben *et al.*, 2020; Verheyen *et al.*, 2020). Another application mentioned in the literature is entomoremediation, where insects are used to carry out *in situ* remediation of various environmental contaminants from soil (Ewuim, 2013). Based on this principle, Bulak *et al.* (2018) explored the possibility of using black soldier flies to remediate plant biomass that had been artificially contaminated with cadmium and zinc. The authors acknowledge that insects used for such applications cannot be subsequently used for human or animal consumption, and they instead propose other ways this mode of metal recovery can be made economically viable.

There are several multi-integrated applications of insects, such as in the case of domesticated silkworms (*Bombyx mori*). The pupae are used as a source of food and animal feed in Colombia and the frass as a fertilizer or feed for aquaculture (FAO, 2013). In India, seriwaste from silkworms is used for biofuel and composting, and in Kenya silkworm pupae are fed to poultry after the silk has been produced and sold (FAO, 2013).

Silkworm cocoons at a sericulture breeding station in Azerbaijan.

A modern, large-scale insect production facility.

FOOD SAFETY CHARACTERIZATION OF INSECTS

Insects might carry biological and chemical contaminants as well as physical hazards that can be detrimental to the health of consumers. These food safety hazards are associated with direct or indirect (via animal feed) consumption of insects. According to the European Food Safety Authority (EFSA), the health risks associated with using insects as food for humans and as animal feed depend on the insect species and their substrate, as well as on how the insects are reared, harvested and processed (EFSA Scientific Committee, 2015; EFSA NDA Panel, 2021). It must be pointed out that the food safety hazards described below apply to numerous foods and not only to insects.

Unlike other livestock, insects are consumed in their entirety which necessitates paying close attention to how insects are farmed and processed. Insects can accumulate contaminants from their feed or housing materials. Due to their small size, it can be difficult to decontaminate harvested insects, and any eventual contamination may be carried along the production and processing chain.

The source of edible insects is also an important consideration as consuming insects that are reared under controlled and hygienic conditions may pose different food safety concerns from insects that have been harvested in the wild (Li *et al.*, 2016; Murefu *et al.*, 2019). While there are food safety hazards associated with raw or unprocessed insects, it is less likely that humans will eat insects in that state (Stoops *et al.*, 2016; Grabowski and Klein, 2017; Garofalo *et al.*, 2019). In order to create and implement insect species-appropriate hygienic practices for rearing, processing, storing and transporting, it is important to characterize the various food safety-related hazards in edible insects.

BIOLOGICAL HAZARDS

While pathogenic microbes of insects (entomopathogenic) are considered harmless to humans and animals due to phylogenetic differences, insects can be a vector for various microorganisms that are detrimental to human and animal health, especially under poorly controlled hygienic conditions (Kooh *et al.*, 2019). The risk of transmitting zoonotic infections to humans through edible insects seems low, but this topic requires greater research to clarify the potential risks for food and feed (Dicke *et al.*, 2020).

The microbiota of insects is complex; it is not just localized in the gut but also on various anatomical parts. This microbiota is comprised of microbes that are either intrinsically part of an insect's life cycle or are introduced during farming and processing (EFSA Scientific Committee, 2015). With some exceptions, insects are usually consumed in their entirety, as removal of the gut is not always possible. In addition, Wynants *et al.* (2017) showed that post-harvest practices like 48-hour starvation followed by rinsing did not affect the composition of the gut microbial community in mealworm larvae. The effects of such practices on the gut microbiota are not known for all edible insect species. In order to facilitate the development of appropriate guidelines to ensure the food safety of the end products, it is important that the microbial species that typically make up the microbiota of edible insects are characterized.

The microbiota of different commercially available, processed[7] insect species have been analyzed through different culture-dependent and

[7] Includes and not limited to dried, boiled or blanched, roasted, smoked and deep-fried.

culture-independent methods. These insects include house crickets (*Acheta domesticus*), locusts (*Locusta migratoria*), yellow mealworm larvae (*Tenebrio molitor*), giant water bugs (*Belostoma lutarium*), black ants (*Polyrhachis*), winged termites (Termitidae), rhino beetles (*Hyboschema contractum*), mole crickets (Gryllotalpidae), silkworms (*Bombyx mori*), among others (Garofalo *et al.*, 2017; Osimani *et al.*, 2018a). The microbial risks associated with edible insects can be greatly controlled by following good hygienic practices during rearing, handling, harvesting, processing, storing and transporting insects and insect-based products.

A qualitative risk assessment to estimate the microbiological risks associated with potentially feeding locally sourced cricket powder to undernourished infants and children (6 to 23 months) was carried out by Walia, Kapoor and Farber (2018). They found that boiling the porridge, fortified with cricket powder, for five minutes prior to consumption reduced the food safety risks associated with *Staphylococcus aureus*, *Bacillus cereus*, *Clostridium perfringens* Type A, *Cronobacter sakazakii*, enterohemorrhagic *Escherichia coli*, *Listeria monocytogenes* and *Salmonella* spp. The authors suggested that many of these microbiological risks can be mitigated if crickets are reared and processed under hygienic conditions.

BACTERIA: Several bacterial species have been associated with edible insects, both farm-reared (EFSA Scientific Committee, 2015; Vandeweyer *et al.*, 2017a) and wild-caught (Braide *et al.*, 2011; Amadi and Kiin-kabari, 2016). These include some bacterial species from the genera *Staphylococcus*, *Streptococcus*, *Bacillus*, *Pseudomonas*, *Micrococcus*, *Lactobacillus*, *Erwinia*, *Clostridium* and *Acinetobacter* as well as members of the family Enterobacteriaceae (EFSA Scientific Committee, 2015; Garofalo *et al.*, 2019; Murefu *et al.*, 2019). Certain members of these genera and family are not only pathogenic and opportunistic bacteria but they can also be responsible for reducing the shelf-life of edible insects.

To reduce the transmission of foodborne pathogens to humans through insect consumption, it is important for insect farms to have strong biosecurity measures and to prevent contact with livestock animals (**Box 2**). *Campylobacter* and *Salmonella* can be isolated from insects that have close contact with affected livestock (Wales *et al.*, 2010; Belluco *et al.*, 2013). More research is needed to understand the behaviour of foodborne pathogens in edible insects. Feeding experiments with houseflies (*Musca domestica*) using *Escherichia coli* O157:H7 has shown that the ingested bacteria can be found in the intestine, the crop and the mouthparts of the insects. The bacteria were found to be excreted for three days post feeding, which shows that the potential for houseflies to spread the bacteria can be high (Kobayashi *et al.*, 1999).

Rearing materials can also determine if there are any potential microbiological risks to consider. For instance, if materials such as paper egg cartons are used for rearing insects, there are risks for contamination with *Salmonella* and *Campylobacter*. Risks are higher if the cartons have been in contact with feces from poultry (Walia, Kapoor and Farber, 2018).

Contamination of edible insects post-processing is also an area of consideration. For instance, edible insects sun-dried in humid areas may be susceptible to microbial growth due to moisture. Air-drying of insects where they may come in contact with soil also pose potential food safety issues. 'Ready-to-eat' insects sold to consumers in many parts of the world are generally roasted or fried, steps that are effective in eliminating foodborne pathogens. However, re-contamination or cross-contamination[8] risks arise if such insects are not hygienically handled or stored before consumption.

Silkworm pupae are fried and served as street food in Thailand.

[8] Cross-contamination occurs when there is transfer of microbes from one surface or object to another.

The presence of endospore-forming bacteria in edible insects is another major food safety concern as the spores, being heat-resistant, may withstand the common processing methods adopted for edible insects, like drying, boiling and deep-frying (Martinez *et al.*, 2007; Klunder *et al.*, 2012; Liu *et al.*, 2015; Osimani *et al.*, 2017a; Vandeweyer *et al.*, 2017b). Spore-forming bacteria like *Bacillus cereus* sensu stricto (s.s.), *B. cytotoxicus*, *B weihenstephanensis* and *Clostridium thermopalmarium* have been found in processed edible yellow mealworms, locusts and house crickets (Osimani *et al.*, 2017a; Vandeweyer, Lievens and van Campenhout, 2020). Some *B. cereus* also include psychrotrophic[9] strains. Therefore, improper cooling after heat-treatment of insects may facilitate conditions for the germination of spores allowing *B. cereus* to multiply and produce toxins. Other lethal toxin-producing, spore forming bacteria like *Clostridium sordellii* have also been identified in edible insects (Osimani *et al.*, 2018a).

[9] Psychrotrophic microorganisms have the ability to grow at low temperatures and some are well-known for their degradative activities of food, causing issues related to safety and quality of food (Gounot, 1986).

BOX 2. TRANSFERABLE ANTIMICROBIAL RESISTANCE GENES AND EDIBLE INSECTS

Transferable antimicrobial resistance (AMR) genes are an emerging concern. Overuse and misuse of antimicrobials in food-producing animals select for resistant microorganisms, which can affect human health. Evidence suggests that insects commonly found on livestock farms can act as vehicles for bacteria that carry AMR genes between farms and urban communities (Zurek and Ghosh, 2014). Recent studies show the occurrence of AMR genes in bacteria from edible insects (Roncolini *et al.*, 2019; Vandeweyer *et al.*, 2019). This includes genetic determinants for conferring resistance to erythromycin, tetracycline, vancomycin, beta-lactams, and aminoglycosides (Osimani *et al.*, 2017b; Osimani *et al.*, 2018b; Roncolini *et al.*, 2019; Vandeweyer *et al.*, 2019). Potential causes include contamination of substrates, water, and/or rearing environments with bacteria resistant to antimicrobials.

Some reported cases of botulism in Africa have been attributed to insect consumption (Schabel, 2010; Knightingale and Ayim, 1980). In addition, several spoilage-causing microbes like *Lysinibacillus* sp. and *Bacillus subtilis*, which can alter the quality of the food product, have been detected in edible insects, raising safety concerns (Vandeweyer, Lievens and van Campenhout., 2020).

Owing to a growing interest in edible insects, consumers are also turning to various online platforms to purchase processed edible insects (for instance, as powder or flour, which is made from dried and ground insects and can be used as an ingredient in baked goods). A few studies on the microbiota associated with processed edible insects from e-commerce showed members of the *Vibrio*, *Streptococcus*, *Staphylococcus*, *Clostridium* and *Bacillus* genera (Fasolato *et al.*, 2018; Osimani *et al.*, 2018a). An appropriate regulatory framework will not only regulate the online trade of edible insects but also ensure the health of consumers.

VIRUSES: So far, risks associated with foodborne viruses, like hepatitis A, hepatitis E and norovirus, from consuming edible insects are low, but care must be taken not to introduce the viruses in insect production units through substrates (Vandeweyer, Lievens and van Campenhout, 2020). Insects can potentially serve as replicative vectors for viruses that infect vertebrates. Additional studies are needed to investigate the possible occurrence and transmission of arthropod-borne arboviruses, which can cause a number of human diseases (e.g. West Nile disease, rift valley fever, chikungunya and hemorrhagic fever) through edible insects (EFSA Scientific Committee, 2015).

FUNGI: Foodborne fungi can be responsible for food spoilage through product quality deterioration and nutritional losses. In addition, some of the fungi are pathogenic to humans and can form mycotoxins that are extremely harmful to humans (covered under *Chemical hazards*).

Yeast, including relatives of *Tetrapisispora*, *Candida*, *Pichia* and *Debaryomyces*, and mould species from *Aspergillus*, *Alternaria*, *Cladosporium*, *Fusarium*, *Penicillium*, *Phycomycetes*, and *Wallemia* are associated with the microbiota found on the body surface or the gut of edible insects and may be harmful (Rumpold and Schlüter, 2013; Osimani *et al.*, 2017a; Schlüter *et al.*, 2017; Kooh *et al.*, 2019).

PARASITIC HAZARDS: Insect species deemed fit for mass production may be vectors for parasites and this hazard must be given due consideration. However, the parasitic risks associated with edible insects that can affect humans are poorly documented. Based on data collected from human autopsies and analyses of insects traditionally consumed in southeast Asia, possible transmission of foodborne intestinal flukes to humans have been suggested. These trematodes belong to the Lecithodendridae and Plagiorchidae families (Chai *et al.*, 2009; Belluco *et al.*, 2013). Certain protozoan species like *Entamoeba histolytica*, *Balantidium* spp., *Isospora* spp., *Giardia lamblia*, *Toxoplasma* spp., and *Sarcocystis* spp. have also been documented in insects that are deemed edible (Graczyk, Knight and Tamang, 2005; Gałęcki and Sokól, 2019). There are some documented cases of intestinal myiases in humans who consumed black soldier fly larvae reared on ripe and unwashed fruits that had been oviposited by flies (Lee *et al.*, 1995; Wang and Shelomi, 2017). Edible insects may also be potential vectors for *Cryptosporidium* spp. and *Trypanosoma cruzi* (Chagas disease) (van der Fels-Klerx *et al.*, 2018; Gałęcki and Sokól, 2019). Coccidia parasites can be found in chicken manure. If insects are reared on poultry manure, appropriate processing steps for the produced insects will need to be established before they are fed to animals.

CHEMICAL HAZARDS

Insects reared on agricultural waste may be exposed to mycotoxins, crop protection chemicals like pesticides and other chemical hazards like toxic metals and dioxins. If livestock and poultry manure is used for insect rearing, they may be exposed to antimicrobials and pesticides. The potential transfer and accumulation of these contaminants in insects, used as human food or animal feed should be carefully considered and addressed by this emerging sector.

MYCOTOXINS: Several mycotoxins have been detected in edible insects, albeit not at levels that give rise to public health concerns (De Paepe *et al.*, 2019). Charlton *et al.* (2015) reported the presence of beauvericin, enniatin A and enniatin A1 in dried housefly (*Musca domestica*) larvae at levels that were not considered to pose a health risk. However, aflatoxins have been documented (highest level 50 µg/kg) in some commercial lots of 'ready-to-eat' mopane worms in Botswana, highlighting the importance of hygienic handling, processing and storing of edible insects (Mpuchane *et al.*, 1996; Mpuchane *et al.*, 2000).

Studies show that when some insect species are exposed to substrates with high levels of certain mycotoxins, the chemical contaminants do not appear to accumulate. They are instead metabolized by the insects or are excreted in the insect frass. In some cases, a difference in mass balance is observed where the quantity of ingested mycotoxins from substrates do not add up to the sum total of levels found metabolized, excreted and in unconsumed feed (Bosch *et al.*, 2017; van Broekhoven *et al.*, 2017; Niermans *et al.*, 2019). Camenzuli *et al.* (2018) reported that none of the four mycotoxins (aflatoxin B1, deoxynivalenol, zearalenone and ochratoxin A), which were added to the insect substrates in levels much higher than European Commission (EC) maximum limits, accumulated in the larvae of black soldier fly and lesser mealworm. While aflatoxin B1, zearalenone and ochratoxin A were

Roasting of mealworms in a processing facility in Republic of Korea.

detected above limit of quantification (LOQ) in the larvae of black soldier fly, the concentrations were several orders of magnitude lower than their corresponding concentrations in the substrates. In addition, zearalenone was metabolized into α- and β-zearalenol, both of which could be detected by analytical means (Camenzuli *et al.*, 2018). In case of lesser mealworm, the concentrations of mycotoxins and their metabolites were found to be below the respective LOQs (Camenzuli *et al.*, 2018). Based on the evidence so far, there may be a species-specific metabolism of mycotoxins that lead to metabolites not yet considered for analysis. More research is needed to better identify the metabolism routes, the metabolites and their potential toxicological effects on human and animal health.

PESTICIDES: Pesticides (**Box 3**) used on agricultural produce may accumulate in insects that are raised on treated plant-based side stream materials (Houbraken *et al.*, 2016). Feeding studies show that that yellow mealworms can accumulate, degrade, enantiomerize and excrete

BOX 3. INSECT CONSUMPTION AS A PEST CONTROL MEASURE COMES AT A RISK

Historically, many communities across the globe have addressed periodic locust swarms that devastated crops in the region by turning them into food in times of severe food scarcity or as animal feed. However, such outbreaks are being increasingly managed with pesticides, for instance large scale pesticide usage to control the recent desert locust swarms in the greater Horn of Africa region, the Arabian Peninsula and Southwest Asia (FAO, 2020). Such measures can make these insects unsafe for consumption by humans or animals . Organophosphate (sumithion and malathion) and chlorinated pesticides (benzene hexachloride, lindane and aldrin) were identified by Saeed *et al.* (1993) in edible locust samples from Kuwait. The pesticides had been used to control locust swarms that invaded the country during the period 1988–89 (Saeed *et al.*, 1993).

several chiral fungicides like metalaxyl, myclobutanil, diniconazole, epoxiconazole and benalaxyl (Liu *et al.*, 2013; Lv *et al.*, 2013; Gao *et al.*, 2013, 2014; Lv *et al.*, 2014). Chlorpyrifos has been identified in housefly samples, albeit at levels that do not pose a safety risk (Charlton *et al.*, 2015). Controlled feeding at edible insect farms should help minimize risks associated with pesticide residues. In addition, to fill in knowledge gaps it will be useful to also determine the chemical processes involved in the degradation and biotransformation of pesticides in edible insect species.

TOXIC METALS: Accumulation of toxic metals by edible insects has been found to be associated with a number of factors including the metal type, insect species, growth phase, the substrates used and environmental contamination (Vijver *et al.*, 2003; Zhang *et al.*, 2009; Greenfield, Akala and Van Der Bank, 2014; EFSA Scientific Committee, 2015). Through feeding trials, accumulation of cadmium has been documented in black soldier fly and field cricket (*Gryllus assimilis*), both of which are of considerable commercial interest (Diener, Zurbrügg and Tockner, 2015; Bednarska *et al.*, 2015; Purschke *et al.*, 2017; van der Fels-Klerx *et al.*, 2020). Cadmium was also found in housefly samples at levels higher than the permissible limit for cadmium in animal feed (500 µg/kg), as per the directive 2002/32/EC (EC, 2002; Charlton *et al.*, 2015).

Black soldier flies also accumulate lead when they are reared on substrates spiked with the heavy metal (van der Fels-Klerx *et al.*, 2016; Purschke *et al.*, 2017). High levels of lead were found in *chapulines* (local name for dried grasshoppers) from the state of Oaxaca, Mexico. This was identified as one of the sources that contributed to elevated blood lead levels during an outbreak of lead poisoning among the migrant population in Monterey

Vehicle spraying pesticides in an area infested with desert locusts in Kenya.

County, California, United States of America (Handley *et al.*, 2007).

Using spiked feeding trials, black soldier flies were shown to excrete most of the arsenic they consumed, in contrast to the larvae of yellow mealworm, which was shown to accumulate it, raising safety concerns (van der Fels-Klerx *et al.*, 2016). In addition the ability of chitin to adsorb heavy metals makes it important to consider the rearing environment of insects (Bailey *et al.*, 1999; Anastopoulos *et al.*, 2017; Boulaiche, Hamdi and Trari, 2019).

For insects to be used as food and feed, maximum levels of certain heavy metals like cadmium, lead, mercury and arsenic need to be evaluated based on insect species.

TRACE METALS: It is also important to pay attention to the levels of trace minerals (iron, manganese, magnesium, copper) obtained from consuming certain edible insect species. Accumulation of high levels of selenium has been reported in yellow mealworm (Hogan and Razniak, 1991). High concentrations of manganese have been found in edible winged termites from Benin, South Africa and Zimbabwe as well as from samples purchased online. Manganese can be toxic in high quantities, and the levels reported signify that 100 g of the insects can provide about 40 times the recommended upper limit for adults (O'Neal and Zheng, 2015; Payne *et al.*, 2015; Verspoor *et al.*, 2020). However, at this point, it still not clear how much of the trace metals are bioavailable upon consumption.

OTHER SUBSTANCES OF CONCERN:

- **FLAME RETARDANTS:** Gaylor, Harvey and Hale (2012) reported bioaccumulation of polybrominated diphenyl ether (PBDE) from polyurethane foams, commonly found in consumer goods, in house crickets (*Acheta domesticus*). Tributylphosphate has also been identified in edible insect samples from Belgium (Poma *et al.*, 2017). Feeding experiments show that mealworms rapidly excrete hexabromocyclododecane (HBCD) in their frass (Brandon *et al.*, 2020). Poma *et al.* (2019) found low levels of contamination (within legal limits in food of animal origin) by various organic compounds (persistent organic pollutants, halogenated flame retardants, organophosphorus flame retardants and plasticizers) in edible insects. These insects belonged to six orders (Orthoptera, Coleoptera, Lepidoptera, Hemiptera, Odonata and Hymenoptera), and were purchased from five European and three Asian countries. The study also emphasized that, apart from activities during the period of rearing the insects, industrial post-harvest handling and the addition of various ingredients (flavours, dressings, among others) play a role in influencing the chemical load of the final insect food product (Poma *et al.*, 2019).

- **DIOXINS:** There is currently insufficient information about the accumulation of dioxins (polychlorinated dibenzo dioxins and dibenzo furans, PCDD/PCDF) and dioxin-like polychlorinated biphenyls (PCB) in edible insects. Using laboratory-based and field studies, Paine, McKee and Ryan (1993) showed that PCBs can accumulate in crickets that are exposed to contaminated soil. Poma *et al.* (2017) studied the concentration of 12 different PCBs in insects and insect-derived products from the Belgian market and found that the concentrations detected in products derived from crickets were within safe limits, according to the legislation in the European Union.

- **MINERAL OILS:** High levels of mineral oil hydrocarbons (MOH) have been observed in black soldier fly (van der Fels-Klerx *et al.*, 2020). As no significant differences were found in the concentrations between control and experimental groups, the authors suggested that these

Frozen bamboo caterpillars sold in supermarkets in Thailand.

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high levels were independent of the substrates fed to the insects. As hydrocarbons are integral components of cuticular lipids of several insects, it is important to understand the native content of MOH in edible insect species reared for food and feed (EFSA CONTAM Panel, 2012).

- **HISTAMINE:** Histamine toxicity (sometimes referred to as scombroid poisoning) cases have been reported in Thailand, which Chomchai and Chomchai (2018) postulated was due to consumption of fried insects (grasshoppers, silkworm pupae).

- **OTHER CHEMICAL CONTAMINANTS FROM PRODUCTION AND/OR PROCESSING:** Contamination by certain chemicals like flame retardants and legacy/emerging plasticizers can occur during production (such as from the rearing substrate, polyvinyl chloride (PVC) from the gloves used by workers at the production facility), industrial processing, storing (for instance in PVC tanks), transporting and/or as a result of direct transfer from food-packaging materials (Poma *et al.*, 2019). Small amounts of packaging materials might remain with food side streams that are intended to be fed to insects and result in chemical contamination of the produced insects. Plastic, resin, aluminium foil and pressed paperboard may be found among the remnants of the packaging materials left with the food side streams (Pinotti *et al.*, 2019).

  Processing insects can also give rise to potentially toxic compounds like heterocyclic aromatic amines, polyaromatic hydrocarbons (PAH), chloropropanols, furans and acrylamide due to chemical or thermal reactions between insects and other ingredients (Fernandez-Cassi *et al.*, 2018). Further evaluation is needed on bioaccumulation of chemical contaminants from processing when considering using insects as food for human consumption (IARC, 1993; van Huis, 2016).

ANTIMICROBIALS: There is limited literature on the use of antimicrobials for managing microbiological and parasitic infections of insects. It is possible that antimicrobials may be added as a contingency measure to control microbiological issues in industrial rearing facilities (EFSA Scientific Committee, 2015). Supplementation of the insect substrate with chloramphenicol has been suggested to treat the "flacherie" disease caused by *Enterococcus mundtii* in silkworms.

This broad-spectrum antimicrobial was found to resist inactivation in the digestive tract of the insects (Cappellozza *et al.*, 2011). Under experimental conditions, streptomycin and chlortetracycline have shown potential to promote better growth in the southern green stink bug (*Nezara viridula*) and in honeybees (Peng *et al.*, 1992; Hirose, Panizzi and Cattelan, 2006). The presence of netilmicin and streptovaricin G in edible insects – honeycomb moth (*Galleria mellonella*), locust (*Locusta migratoria*), house cricket (*Acheta domesticus*) and lesser mealworm (*Alphitobius diaperinus*) – which are commercially available in Belgium, has been reported in the literature (Poma *et al.*, 2017).

ALLERGENIC POTENTIAL: Insect-based foods may pose potential allergenic risks to consumers, particularly those who are allergic to crustaceans due to cross-reactivity (Reese, Ayuso and Lehrer, 1999; Srinroch *et al.*, 2015). Severe allergic reactions to yellow mealworms in patients allergic to shellfish have been verified by double-blind, placebo-controlled food challenge trials conducted by Broekman *et al.* (2016). It has been suggested that people with shrimp allergies could be at a risk of food allergy not only for mealworms (*Tenebrio molitor*, *Alphitobius diaperinus* and *Zophobas morio*) but most likely also for other insects (Broekman *et al.*, 2017b). Known panallergens that cause cross-reactive allergies include arginine kinase, tropomyosin, glyceraldehyde-3-phosphate dehydrogenase, hexamerin1B, sericin and haemocyanin (Belluco *et al.*, 2013; Phiriyangkul *et al.*, 2015; Srinroch *et al.*, 2015; Ribeiro *et al.*, 2018; Leni *et al.*, 2020). It has been suggested that larval cuticle proteins A1A, A2B and A3A in mealworms are primarily responsible for the mealworm allergy. This allergic reaction was studied in individuals who had no clinical allergy to shrimp, which means that the larval cuticle proteins induced a potential de-novo sensitization (Broekman *et al.*, 2017a). While established methods for allergenic risk assessment can be used to ascertain homologous or cross-reactive allergens from alternative food sources, determination of yet unknown allergens from insects will need the development of additional tools (Westerhout *et al.*, 2019).

Processing of insects may also play a role in increasing or decreasing the allergenicity of insects. Phiriyangkul *et al.* (2015) found that the allergenicity of arginine kinase and enolase decreased while that of glyceraldehyde-3-phoshate dehydrogenase increased following thermal processing of Bombay locusts (*Patanga succincta*).

Although specific insect allergens are largely unknown, there are a few reported cases of allergic reactions associated with entomophagy. Okezie, Kgomotso and Letswiti (2010) has reported an allergic reaction associated with the consumption of mopane worm (*Imbrasia belina*) in Botswana. There are anaphylactic shock cases associated with consuming silkworm pupae (Ji *et al.*, 2008; Gautreau *et al.*, 2017).

People with known allergies to house dust mites (via inhalation) in addition to crustaceans may also be allergic to edible insects like yellow mealworm, house cricket, and desert locust (*Schistocerca gregaria*) (Verhoeckx *et al.*, 2014; Pali-Schöll *et al.*, 2019). Freye *et al.* (1996) reported anaphylactic shock following the consumption of yellow mealworm by an individual with a known inhalant allergy to beetle larvae.

Retail packaging of silkworm pupae in Viet Nam.

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Allergic reactions to insects via inhalation or skin contact have also been documented (Park *et al.*, 2014). Workers on the insect farms may be prone to experiencing adverse reactions at their job sites. There are recorded instances of insect-farm workers developing work-related allergic reactions to members of the orders Coleoptera (mealworms) and Orthoptera (locusts and grasshoppers) (Bernstein, Gallagher and Bernstein, 1983; Pener, 2014).

Studies suggest that chitin, commonly found in exoskeletons of invertebrates like crustaceans, insects, and house dust mites, may induce allergic reactions through inhalation (Lee *et al.*, 2008; Brinchmann *et al.*, 2011). Research is needed to determine if there is any association between this mode of allergenic potential of chitin and consumption of insects.

INHERENT SUBSTANCES OF CONCERN: Insects can produce certain noxious substances or can accumulate them from their environment (EFSA Scientific Committee, 2015). Some of these substances can impact the bioavailability of nutrients from insects by acting as chelators that bind to minerals and, therefore, interfere with their absorption. Examples of the known "anti-nutritional" substances in insects are thiaminase, phytic acid, tannins, oxalates, saponins, quinones, phenolic compounds, cyanogenic glycosides and toluene (Belluco *et al.*, 2013; NVWA, 2014; ANSES, 2015; Chakravorty *et al.*, 2016; Dobermann, Swift and Field, 2017).

Few studies show that the levels of these substances in some of the commonly consumed insects are very low (Ekop, Udoh and Akpan, 2010; Shantibala, Lokeshwari and Debaraj, 2014). However, it is important to note that consumption of such substances may be particularly harmful for people who suffer from poor diets and consume insufficient nutrients.

Thiaminase found in *Anaphe* spp. can cause deficiency issues by breaking down thiamine (vitamin B1). People deficient in vitamin B1 are, therefore, especially susceptible. Seasonal ataxia has been reported in Nigeria due to the consumption of roasted larvae of *Anaphe venata*, an alternative protein source commonly consumed in the western part of the country. The symptoms of seasonal ataxia are often completely treated by administering high doses of thiamine infusions (Nishimune *et al.*, 2000; Moyo *et al.*, 2014).

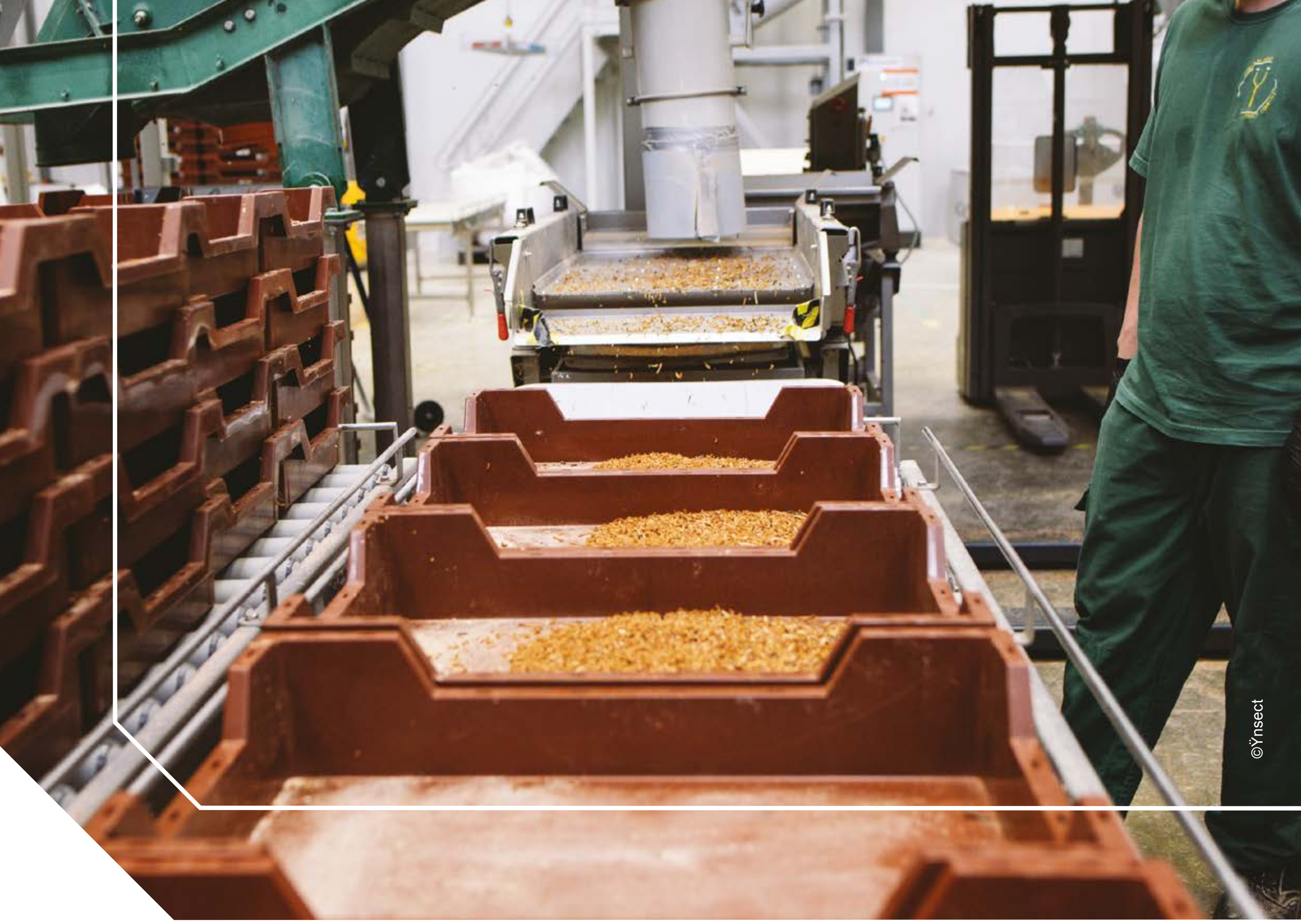
Cyanogenic[10] glycosides release hydrogen cyanide upon degradation. Low levels of cyanogenic glycosides (23–140 µg/100 g) have been reported in wild harvested and processed *Eulepida mashona* and edible stinkbugs (Masundire *et al.*, 2014, 2016). However, at these levels they are not expected to cause any food safety issues. While adequate processing of insects can result in a reduction of these substances in edible insects, more comprehensive analyses are needed to investigate their occurrence levels and determine the human health effects of these substances and other toxins potentially produced by edible insects.

PHYSICAL HAZARDS

Dehydrated insects consumed whole can pose physical hazards due to the hard parts of the insects, such as stings, wings, rostrum, and spines on shinbones which can cause physical obstructions. Consumers must be informed of the presence of these insect parts in the food products (ANSES, 2015).

Locusts collected after a swarm in Madagascar. Typically wings and hind legs are removed before being fried.

[10] Provisional maximum tolerable daily intake (PMTDI) for cyanogenic glycosides was set at 20 µg/kg body weight/ day, according to the Seventy Fourth Joint FAO/WHO Expert Meeting on Food Additives, 2012.



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At an insect production facility, employees check the feeding process of insects (above) and insect trays (below).

OVERVIEW OF REGULATORY FRAMEWORK FOR INSECTS

The areas where entomophagy is widespread are in places where it is generally practiced as a local tradition and it tends not to be overly regulated. In some countries where insects are not usually perceived as human food or animal feed products, legislation tends to refer to insects as impurities or pests that contaminate food. The lack of specific legislation for insects as food or feed products in many high-income nations stems from the fact that the scale of insect production has been quite limited and the sector is still niche in scope. Recently, however, a growing interest in using insects for human and animal consumption as well as other applications is fueling industrial-scale insect farming in different regions. Yet most countries still lack precise and insect-specific legislation, standards, labelling and other regulatory instruments to govern the production and commercialization of insects in both food and feed supply chains. This lack of a regulatory framework is a major barrier in the way of establishing markets for insects and insect-based products.

INTERNATIONAL STANDARDS: CODEX ALIMENTARIUS

The Codex Alimentarius is a collection of international standards, guidelines and codes of practice aimed at protecting the health of consumers as well as ensuring fair practice in the international food trade. While recommendations made by the Codex are considered voluntary by Member Countries, national legislation is often created based on the standards established under the Codex. Indeed, the Codex

41st Codex Alimentarius Commission.
FAO headquarters, Rome, Italy.

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is recognized as the benchmark for food safety in the World Trade Organization's Agreement on Sanitary and Phytosanitary measures, which means that Codex standards have far reaching implications for resolving trade disputes.

Discussions about introducing international standards for the edible insect sector have been limited at the Codex level. The 17th FAO/WHO Codex Alimentarius Coordinating Committee for Asia (2010) considered a proposal to develop a Codex regional standard for edible house crickets (*A. domesticus*) and cricket-based products (CX/ASIA 10/17).[11] This consideration was based on the historical prevalence of entomophagy in several countries and a growing global interest in using insects as a food source. However, the Coordinating Committee decided to discontinue work on this subject in 2014 as there were insufficient data to support new work on edible insects; particularly related to the production, consumption and trade of these products (international and regional) as well as inadequate food safety risk assessment data on edible insects (CX/ASIA 14/19).[12]

REGIONAL AND NATIONAL LEGISLATION

THE EUROPEAN UNION

Since January 2018, all insect-based products (whole insects, their parts or extracts) meant for human consumption have fallen under the

[11] Report of the Seventeenth Session of the FAO/WHO Coordinating Committee for Asia. Bali, Indonesia. 22–26 November 2010. http://www.fao.org/fao-who-codexalimentarius/committees/codex-regions/ccasia/meetings/en/. Accessed 23 October 2020.

[12] Report of the Nineteenth Session of the FAO/WHO Coordinating Committee for Asia. Tokyo, Japan. 3–7 November 2014. http://www.fao.org/fao-who-codexalimentarius/committees/codex-regions/ccasia/meetings/en/. Accessed 23 October 2020.

novel food regulation EU 2015/2283.[13] This implies that it is necessary to apply specifically to the European Commission (EC), with a follow-up scientific evaluation by EFSA (**Box 4**), before putting an insect-based product on the market. Some of the applications[14] under consideration are flours made from house crickets (*A. domesticus*), migratory locusts (*L. migratoria*), yellow mealworms (*T. molitor*) among others. Overviews of the approval process to be followed for edible insects, based on this novel food regulation, are available (EFSA NDA Panel, 2016a; Belluco *et al*., 2017; IPIFF, 2019a). Under the Notification Procedure, insect food business operators in the European Union may have their products authorized as "novel foods" if the edible insects of interest are identified as traditional food from third countries with a history of safe use (25 years of uninterrupted consumption). Such products can be placed

BOX 4. YELLOW MEALWORMS – FIRST INSECT APPROVED BY EFSA UNDER THE EUROPEAN UNION NOVEL FOODS REGULATION

According to a recent risk assessment carried out by EFSA, thermally dried yellow mealworm (*T. molitor*) larvae were found to be safe for human consumption, both in its whole form and as a powder (EFSA NDA Panel, 2021). This evaluation was in response to a novel food application for dried yellow mealworm submitted by EAP Group SAS – Agronutris, a French insect production company, to the EC.

[13] EU Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on Novel Foods, Amending Regulation (EU) No 1169/2011 of the European Parliament and of the Council and Repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001; EU: Brussels, Belgium, 2015.

[14] EC Summary of applications and notifications. https://ec.europa.eu/food/safety/novel_food/authorisations/summary-applications-and-notifications_en. Accessed 5 January 2021.

on European Union markets within four months of the date of submission of a valid and complete notification by the EC to the member states and EFSA, provided that no safety concerns are raised by EFSA or other European Union member states within that period (EFSA NDA Panel, 2016b; Lähteenmäki-Uutela *et al.*, 2017).

Though neither insects nor insect-derived ingredients are listed in Annex II of the Food Information to Consumers regulation (substances or products causing allergies or intolerances), food business operators are strongly advised to state the similarity of allergenicity between insects and crustaceans as well as to dust mites on the products (IPIFF, 2019b).

In the European Union, farmed insects have the status of "farmed animals"[15] and regulations that apply to animal livestock health and biosecurity measures on transmissible diseases also apply to farmed insects.[16] While some insect species can convert waste to a biomass of economic value, insects meant as food cannot be reared on waste streams (household or catering food waste, foodstuff containing meat and fish, manure).

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[15] EU Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 Laying Down Health Rules as Regards Animal By-products and Derived Products not Intended for Human Consumption and Repealing Regulation (EC) No 1774/2002 (Animal By-products Regulation); EU: Brussels, Belgium, 2009.

[16] EU Regulation (EC) No 2016/429 of the European Parliament and of the Council of 9 March 2016 on Transmissible Animal Diseases and Amending and Repealing Certain Acts in the Area of Animal Health ("Animal Health Law"); EU: Brussels, Belgium, 2016. EU Regulation (EC) No 2016/429 of the European Parliament and of the Council of 9 March 2016 on Transmissible Animal Diseases and Amending and Repealing Certain Acts in the Area of Animal Health ("Animal Health Law"); EU: Brussels, Belgium, 2016.

To prevent issues related to spongiform encephalopathies,[17] processed animal proteins (blood products, gelatine, collagen, hydrolyzed proteins of animal origin and derived from ruminants) cannot be used as a substrate for insects. There are some exceptions, such as processed animal protein products from seven insect species (*Hermetia illucens*, *Musca domestica*, *Tenebrio molitor*, *Alphitobius diaperinus*, *Acheta domesticus*, *Gryllodes sigillatus* and *Gryllus assimilis*) that currently can be used as part of the formulation for aquaculture feed and pet food in the European Union.[18]

A recently published document lays down the analytical method to distinguish between the presence of these insects in aquaculture feed as opposed to others that are not allowed (Garino, Zagon and Braeuning, 2019). Maximum levels and guidance values of contaminants that apply to animal feed also apply to farmed insects being used as feedstock for animals (Schrögel and Wätjen, 2019).

If genetic modifications were to be carried out on insects, which are then to be used as food or feed, the products would be governed by the genetically modified organism food and feed regulation[19] (Lähteenmäki-Uutela *et al.*, 2017).

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[17] EU Regulation (EC) No 999/2001 of the European Parliament and of the Council of 22 May 2001 laying down Rules for the Prevention, Control and Eradication of Certain Transmissible Spongiform Encephalopathies; EU: Brussels, Belgium, 2001.

[18] EU Commission Regulation (EU) 2017/893 of 24 May 2017 amending annexes I and IV to Regulation (EC) No 999/2001 of the European Parliament and of the Council and annexes X, XIV and XV to Commission Regulation (EU) No 142/2011 as Regards the Provisions on Processed Animal Protein; EU: Brussels, Belgium, 2017.

[19] EU Regulation (EC) No 1829/2003 of the European Parliament and of the Council of 22 September 2003 on Genetically Modified Food and Feed.

AFRICA

While various insect species are consumed in many African countries, there appears to be a lack of specific regulatory frameworks for using insects as food (Grabowski *et al.*, 2020). There are some exceptions, for instance mopane caterpillars (*Imbrasia belina*) are considered edible according to Botswana's food law (Grabowski *et al.*, 2020). In South Africa, insect (termites and black soldier fly maggots) farming is mainly carried out for use as animal feed (Niassy *et al.*, 2018). Recently, the Kenya Bureau of Standards (KEBS) approved three National Standards that will guide the primary production of edible insects and their processed by-products. Guidelines for insect farmers on how to ensure the safety of the harvested produce by specifying the necessary minimum infrastructure and environmental requirements are provided by KS 2921:2020.[20] The Standards KS 2922 Parts 1[21] and 2[22] provide requirements to be followed for products (food and feed) that contain processed edible insects.

NORTH AMERICA

UNITED STATES OF AMERICA

Food uses of edible insects, insect parts or derivatives fall within the oversight of the United States of America Food and Drug Administration (FDA). As such, edible insects and insect-based food products are required to comply with the Federal Food, Drug, and Cosmetic Act

Woman selling dried caterpillars at a market in the Congo.

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[20] KEBS. Production and handling of insects for food and feed – Code of practice (DKS 2921:2020) https://www.kebs.org/images/standards/public_review_standards/2020/June/DKS_2921_Code_of_Practice_PR.pdf.

[21] KEBS. Edible insects Part 1: Edible insects' products – specification (DKS 2922-1: 2020) https://www.kebs.org/images/standards/public_review_standards/2020/June/DKS_2922Part_1_2020_Edible_Insects_products_PR.pdf.

[22] KEBS. Edible insects Part 2: Products containing edible insects – specification (DKS 2922-2: 2020) https://www.kebs.org/images/standards/public_review_standards/2020/June/DKS_2922_2_Products_containing_edible_insects_PR.pdf.

(FD&C Act) and its implementing regulations. For example, if insects and insect derivatives are to be used as food additives or as color additives, these uses must be approved by FDA [21 U.S.C.§ 348;[23] 21 U.S.C. 379e.[24]]. In addition, edible insects and insect-based products must not be adulterated and their processing, packaging, storage, and transportation must occur under proper sanitary conditions. Insect food products are required to have appropriate labeling on the packaging which includes the common or usual name of the product and its ingredients.

CANADA

Edible insects are regarded as non-novel when considered for use as a food or food ingredient. Silkworms, house crickets and mealworms can be found under the List of Non-novel Determinants for Food and Food Ingredients[25] as determined by Health Canada. Insects produced for the consumption of Canadian consumers must meet the same safety and hygiene standards[26, 27] as other foods available in the country.

Insect-based pet food is available on the Canadian market. Pre-

[23] https://www.govinfo.gov/content/pkg/USCODE-2010-title21/pdf/USCODE-2010-title21-chap9-subchapIV-sec348.pdf, Accessed 2 September 2020.

[24] https://www.govinfo.gov/content/pkg/USCODE-2010-title21/pdf/USCODE-2010-title21-chap9-subchapVII-partB-sec379e.pdf. Accessed 2 September 2020.

[25] Government of Canada. List of non-novel determinations for food and food ingredients https://www.canada.ca/en/health-canada/services/food-nutrition/genetically-modified-foods-other-novel-foods/requesting-novelty-determination/list-non-novel-determinations.html. Accessed 12 December 2020.

[26] Government of Canada. Canadian Food and Drugs Act, Section 4(1) https://laws-lois.justice.gc.ca/eng/acts/f-27/. Accessed 29 December 2020.

[27] Government of Canada. Safe Food for Canadians Act https://laws-lois.justice.gc.ca/eng/acts/s-1.1/page-1.html#h-429388. Accessed 29 December 2020.

Chapulines (toasted or dried grasshoppers) available for purchase at a sporting event in the United States of America.

market authorization/registration[28] are required for insect-derived feed ingredients used as macro-nutrients in animal feed. Under this process, insect-based animal feed ingredient producers are needed to provide information regarding pre-market safety assessment and efficacy, growth substrates, and all manufacturing processes involved for each insect to the Canadian Food inspection Agency (CFIA) before the product is reviewed for approval (Einstein-Curtis, 2019). In 2016, the use of dried whole black soldier fly larvae was authorized as a feed ingredient for poultry broilers (Globe Newswire, 2016).

MEXICO

Wild-collected insects are commonly consumed in the country and, in general, the edible insect trade and marketing are largely unregulated. While harvesting grasshoppers for food and feed is seen as a form of informal pest control for crops like corn, bean and alfalfa, it has been reported that local populations from certain areas that grow genetically modified crops tend to avoid harvesting insects from their fields due to fears about health impacts from consuming insects that feed on the crops (Cerritos and Cano-Santana, 2008; Lähteenmäki-Uutela *et al.*, 2017)

Certain states like Oaxaca have local initiatives that are involved in farming insects. Regulations that govern livestock production also apply to insect farming.[29] There are no specific regulations for insects to be used as animal feed. The policies governing the safety of animal feed are expected to apply to insects (Lähteenmäki-Uutela *et al.*, 2017).

Chinicuiles, a traditional Mexican dish prepared with red maguey worms.

[28] Government of Canada. Registration requirements for insect-derived livestock feed ingredients (draft) https://www.inspection.gc.ca/animal-health/livestock-feeds/consultations/registration-requirements/eng/1557837434904/1557837435158. Accessed 29 December 2020.

[29] Production animal: Crianza de animales terrestres domesticados, incluyendo insectos, epecies acuiticas de agua dulce, salobre o salada.

If edible insects are genetically modified, rules of the "Ley de Bioseguridad de Organismos Genéticamente Modificados"[30] would have to be followed.

OCEANIA

AUSTRALIA AND NEW ZEALAND

While insects have been traditionally consumed by Australian Aboriginal peoples, farming insects for commercial use is only just emerging. According to the Food Standards Australia New Zealand (FSANZ) Advisory Committee on Novel Foods (ACNF),[31] *Z. morio*, *T. molitor* and *A. domestica* are considered non-traditional food, but not novel food. This indicates that they need to comply with the regular Food Standards Code,[32] and it provides some degree of freedom from pre-market approval requirements. While no safety concerns have been identified for the three species, the ACNF meeting in March 2019 updated the allergenicity concerns about crickets to indicate a food allergy risk for individuals allergic to crustaceans. As for insect-based animal feed products, they are currently fed to poultry, used in aquaculture and in select pet foods, but are not fed to ruminants.

ASIA

There is a long-standing tradition of consuming insects in several Asian countries, with insect farming carried out in numerous countries including Cambodia, Lao People's Democratic Republic, Malaysia, Republic of Korea, Thailand, and Viet Nam (Durst and Hanboonsong,

[30] Law on Biosafety of Genetically Modified Organisms; Published in the Diario Oficial de la Federaci6n el 18 de marzo de 2005.

[31] Record of views formed in response to inquiries https://www.foodstandards.gov.au/industry/novel/novelrecs/Documents/Record%20of%20views%20updated%20July%202020.pdf. Accessed 1 September 2020.

[32] Food Standards Code https://www.foodstandards.gov.au/code/Pages/default.aspx.

2015; Reverberi, 2020). While there are no specific regulations for insects used as food in most of these countries, laws that apply to food safety and quality also tend to govern the use of insects, for instance in Malaysia[33] and Thailand (see below). In Republic of Korea, the Government has established some legal measures to support the insect sector[34] with the aim of providing financial benefits to farmers as well as to the national economy. Regulations governing the insect sector in China and Thailand are described below.

CHINA

In many parts of China, there are numerous edible insect species that have been traditionally consumed (Yi *et al.*, 2010). Silkworm pupae was included in the list of food allowed by the Ministry of Health in 2014. While there are no nationwide laws or standards for edible insects, there are local standards available. For instance, in 2016 the Guangxi Zhuang Autonomous Region enacted local food safety standards for edible frozen fresh silkworm pupae (DBS45/030 – 2016) (Lähteenmäki-Uutela *et al.*, 2017). These standards specify the hygienic requirements for producing, processing, transporting and storing as well as labelling and inspection methods for edible silkworm pupae.

THAILAND

In Thailand, edible insects fall under the Food Act B.E. 2522 (1979),[35] which is the general law that governs food quality and integrity.

Fried insects on sale at a market in China.

©Yu Ding/Shutterstock

[33] Laws of Malaysia. Act 281. Food Act 1983. https://www.ecolex.org/details/legislation/food-act-1983-act-281-lex-faoc027309/#:~:text=This%20is%20an%20Act%20to,sale%20and%20use%20of%20food. Accessed 23 January 2021.

[34] Republic of Korea. Act on Fosterage and Support of the Insect Industry http://extwprlegs1.fao.org/docs/pdf/kor113220.pdf. Accessed 23 January 2021.

[35] Food Act (B.E. 2522) http://www.fao.org/faolex/results/details/en/c/LEX-FAOC064932. Accessed 5 January 2021.

The Food and Drug Administration, under the Ministry of Public Health, is the main authoritative body responsible for regulating insect production and consumption (Halloran et al., 2015). In 2017, the Thai National Bureau of Agricultural Commodity and Food Standards (ACFS) from the Ministry of Agriculture released guidelines for cricket farming.[36] The document contains information on how farmers can rear crickets in a safe and efficient manner with processing facilities operating in compliance with correct standards. Another set of guidelines was established in 2012, which provided guidance on rearing silkworms (Bombyx mori) for silk production.[37]

[36] Good Agricultural Practices for cricket farming https://www.acfs.go.th/standard/download/GUIDANCE_GAP_CRICKET_FARM.pdf (in Thai). Accessed 5 January 2021. An unofficial English translation of the document was made by Bugsolutely, a cricket pasta producer, and it can be found at https://www.bugsolutely.com/good-agricultural-practices-gap-cricket-farming/. Accessed 5 January 2021.

[37] Good Practices for Silk Cocoon Production https://www.acfs.go.th/standard/download/eng/GAP_cocoon.pdf. Accessed 5 January 2021.

Vertical farm and processing facility producing ingredients, made from insects, for the food industry.

CHALLENGES OF THE INSECT SECTOR

The practice of rearing insects on a mass scale is still in its early stages. Bringing a novel nutrient source for both food and feed from a niche market into the mainstream has its challenges. Some of the major challenges are described below.

ACCEPTANCE OF INSECTS AS FOOD AND FEED

One of the misconceptions commonly associated with insect consumption is that it is only practised by socially and economically vulnerable groups, especially under conditions of food shortage. In fact, insects are part of the staple diet in many regions where they are consumed for their taste, their nutritive value and are sometimes even considered delicacies. They have, however, not been part of the Western diet; therefore, overcoming food neophobia among some consumers, especially in the Western countries, is a challenge for the edible insects sector (Hartmann *et al.*, 2015; Verbeke, 2015; La Barbera *et al.*, 2018; Bessa *et al.*, 2020). A growing number of behaviour studies have investigated the willingness of consumers to try insect-based products (Hartmann *et al.*, 2015; Verbeke, 2015; Gmuer *et al.*, 2016; House, 2016; Verneau *et al.*, 2016; Gere *et al.*, 2017; Lombardi *et al.*, 2019; Sogari *et al.*, 2019). Based on the research, several suggestions have been put forth, such as strengthening communications related to the benefits of eating insects, incorporating insects into familiar food items (pasta, protein bars, tortilla chips etc.) instead of marketing whole insects, and perhaps even producing visually appealing insect-based

Cricket flour can be used for preparing baked products.

products using 3D printing (Caporizzi, Derossi and Severini, 2019). On the other hand, consumer perception regarding the use of insects as animal feed is largely positive – presumably because it is known that numerous farmed animals consume insects in nature. For instance, Ferrer Llagostera *et al.* (2019) found that consumers in Spain were willing to accept fish that were raised on insect-based feed.

The costs associated with insect-based products pose another hurdle. In the west, the price of insect protein is currently higher than conventional protein sources (Skrivervik, 2020). Upscaling insect production is expected to bring these costs down. Easy availability of edible insects to consumers is also an issue. Edible insects and products containing them can be purchased online in some countries. However, they are not usually found in most supermarket chains, which can provide increased visibility to such products as well as being convenient places for interested consumers to buy them.

Farmers that raise livestock and poultry and have aquaculture facilities can be educated on the pros and cons of using insect-based feed. Such measures are needed to transform the market in the animal feed chain. A study by Chia *et al.* (2020) found that the attitudes of Kenyan farmers toward using insect-based feed can be improved by enhancing extension support services that give them information about the advantages of insect-based feed and existing market opportunities.

REGULATORY HURDLES

Barring a few regions, there is an absence of international regulatory frameworks to support production, risk assessments, quality control measures, and commercialization of insects. Regulations remain one of the major hurdles of the insect sector globally. Some regions are developing regulations for trading in edible insects. For instance, recent

European legislation[38] amended the list of third countries or regions allowed to export edible insects to the European Union to now include Thailand in addition to Canada, Switzerland and Republic of Korea. However, cross-border trading in insects between most countries remains relatively unregulated. In addition, owing to the smaller scale of the international trade in insects (as food or feed) when compared to other commodities, there is also a lack of statistical data on the contribution of insects to trade and the economy.

Since the quality of substrates affect the nutritional and safety aspects of insects, this area requires legislative oversight. In case food side-streams are intended to be used to rear edible insects, regulations on the suitability and safety requirements of this source must be laid out. To this end, national competent authorities should clarify the categories of substrates authorized for insects used for food and feed.

Clear regulations on procuring the first batch of “breeder” insects for starting colonies at production farms will be needed. This will ensure that appropriate risk assessments are carried out at the source and will reduce safety concerns down the line. With insect farming ranging from small farms to industrial scale production, from rural to urban settings, it is necessary to establish good manufacturing practices that can be applied to different production styles. In addition, insect-specific standards would need to be developed by focusing on those species that have been shown to be more promising for domestication.

38 EU Commission Implementing Regulation (EU) 2020/1572 of 28 October 2020 amending Implementing Regulation (EU) 2019/626 as regards lists of third countries and regions thereof authorized for the entry into the European Union of dairy products and insects. EU: Brussels, Belgium, 2020.

RESEARCH GAPS REGARDING FOOD SAFETY

Further research is needed to establish shelf-stability and safety of insect-based products used both in human food and animal feed. There is also limited literature on the toxicological (both *in vitro* and *in vivo*) and safety aspects of various insect-based products like proteins and oils (Zhou and Han, 2006).

It is vital to determine in detail the allergenic potential of certain insects since in addition to being a food safety issue, this may well become an occupational hazard for the sector as well. As the use of edible insects increase, there may arise the need to address the handling of insect-based ingredients in food production and processing facilities. As with allergen ingredients, preventative measures may need to be implemented to avoid cross-contact issues.

As the sector is still young, systematically collected data on insect consumption by both humans and livestock is scarce. In the future, such information will improve our understanding of the benefits of insect-based products, as well as the possible exposure to contaminants, both microbiological and chemical. Additionally, while the risk of transmitting zoonotic infections to humans through edible insects seems low (Dicke *et al.*, 2020), this topic requires greater investigation.

Though insects are considered more sustainable and more environmentally friendly than conventional livestock, there is limited LCA-based research on the production systems themselves. To date LCAs have been published only for a few insect species: mealworms, black soldier fly, house cricket and housefly (Oonincx and de Boer, 2012, Miglietta *et al.*, 2015; Roffeis *et al.*, 2015; Smetana *et al.*, 2016; Halloran *et al.*, 2017a; Salomone *et al.*, 2017; Smetana, Schmitt and Mathys, 2019). While the poikilothermic nature of insects allows for their high feed conversion efficiency, this also means that climate controlled ambient conditions must be maintained in insect rearing systems, especially in cooler areas, through high energy input. In case this energy is derived from fossil fuels, this process could contribute to GHG emissions (Halloran *et al.*, 2016).

Manure generated by livestock and poultry harbors a wide array of microorganisms, including those that are pathogenic to humans and animals. In addition, it also contains veterinary antimicrobials and chemical contaminants like disinfectants, pesticides, among others. While there are studies to show the suitability of using manure to rear insects like black soldier fly or house fly, there is insufficient research to show the nutritional and safety aspects of the produced insects (Oonincx, van Huis and Loon, 2015; Hussein *et al.*, 2017; Miranda, Cammack and Tomberlin, 2019). This knowledge gap needs further research before utilizing this particular waste material as a substrate in insect farming. Another source of substrate that needs detailed safety investigation is slaughterhouse by-products.

PRODUCTION CONCERNS

SCALE: Currently, the scale of global insect production is not large enough to compete with conventional food and feed sources. To be considered a sustainable nutrient source at a global level would require a massive increase in production volumes at a scale that is much larger than the current combined amounts from wild-harvesting and farming. However, scaling up can be an expensive process with investments needed to build facilities (Gahukar, 2016).

Boxes used for raising crickets in Thailand.

In addition, since certain processes in insect-farms are quite labor-intensive, scaling up may also require more investment in terms of increased staff or financing upgrades to include greater automation. In fact, certain large-scale production facilities are now almost fully automated along the entire production cycle. Overall, the scaling up of insect production would need to be optimized from a nutritive, food/feed safety, environmental as well as economic standpoint. However, the sustainability aspects and environmental impacts of upscaling insect production has not yet been given due consideration (Berggren, Jansson and Low, 2019). Genetic modification of insects to increase production is yet another area that must be given thorough consideration, including establishing appropriate regulatory frameworks.

SUBSTRATES: The high cost of commercial feed is disadvantageous to the insect farming sector. Therefore, the concept of rearing insects on agricultural side streams has gained some prominence as a way to provide low-cost substrate to insects as well as a waste management option from a circular economy perspective. However, most side stream materials that are permitted for use as insect substrates already have other pre-determined applications, which can create competition for resources. This is especially true under climate change conditions where drought in certain regions may result in diverting side streams to be used for the more profitable conventional livestock sector. In addition, scaling up production of edible insects would also imply procuring a sustainable and safe source of substrate for the farmed insects. If this substrate is similar to the diet fed to livestock, it may again lead to competition for the same resources. Therefore, the use of substrates which are best upcycled through insect farming may need to be further incentivized.

BIOSECURITY RISKS: Adequate precautions should be taken to ensure that insects do not escape from the production facilities. Certain insect species considered for food and feed are also considered as pests and carriers of foodborne diseases, for instance cockroaches and houseflies. If the insect species being farmed is not endemic to the area and can survive in nature if it escaped, then it is likely to impact the ecosystem in the area. This raises concerns related to plant, animal and human health as well as biodiversity issues (van Huis and Oonincx, 2017). The use of such insect species for rearing purposes should be re-evaluated in depth and governed by a regulatory framework. It is also important to consider strict biosecurity measures if genetic modifications are carried out on insect species of interest. If insects are farmed in outdoor enclosures, it is imperative that the rearing containers are soil-free and adequate measures are taken to prevent contact with feces from birds and rodents.

RESEARCH GAPS: Research is needed into pathogens and parasites that can infect insect species of interest and cause production losses (Gałęcki and Sokól, 2019). For instance, *Acheta domesticus* densovirus (Parvoviridae) have been reported to have decimated commercial house cricket rearing facilities in Europe and North America (Szelei *et al.*, 2011; Weissman *et al.*, 2012). More investigation in this area may also promote prudent use of antimicrobials. In an effort to train a new generation of scientists who can prevent and manage diseases in commercial insect production systems, the Insect Doctors programme[39] was launched in 2020 in the European Union.

Developing tools and standardized methods to verify authenticity of insect-based products i.e. determining whether the contents inside

[39] Insect Doctors Programme, https://www.insectdoctors.eu/en/insectdoctors.htm. Accessed 23 January 2021.

an insect-based product package truly matches the label outside is an important area to consider (Siozios *et al.*, 2020). Mislabeling of insect-based products will not have implications for consumer confidence but it may also have food safety impacts, especially in terms of allergy risks.

GOOD HYGIENE PRACTICES: Implementing good farming and hygiene practices by insect producers is key to avoiding and mitigating the possible occurrence of many of the hazards described in the food safety characterization chapter. A recently released publication provides a practical management guide to cricket farmers as well as a framework for government agencies to monitor cricket production processes while ensuring food safety (Hanboonsong and Durst, 2020). The International Platform of Insects for Food and Feed (IPIFF) has developed the *Guide on good hygiene practices for European Union (EU) producers of insects as food and feed* in line with the European Union regulatory requirements, which is soon to be submitted to the EC for approval.

FINANCIAL INVESTMENTS: Despite growing interest in the sector, procuring investments can be difficult for start-up companies owing to unclear regulations about the production and commercialization of insects as food and feed. This may also have implications on the advancement of research and development in the field.

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A black soldier fly rearing facility in Thailand.

THE WAY FORWARD

A GROWING INTEREST IN INSECTS AS FOOD AND FEED IS SPURRING MASS PRODUCTION OF INSECTS

Due to rising growing global population and food insecurity issues, attention is increasingly being paid to alternative food and feed sources, like insects, that are nutritionally sound and environmentally sustainable. Insects are usually collected from the wild but have begun to be produced in mass-rearing facilities. Insect farming presents several significant benefits to the agri-food industry as well as opportunities to implement circular economy solutions. While still considered niche today, this sector is steadily expanding and is propelled by growing investments and interest, leading to the establishment of more insect-farming and processing companies in various parts of the world.

A THOROUGH ASSESSMENT OF FOOD SAFETY HAZARDS WILL HELP TO ESTABLISH APPROPRIATE HYGIENE AND MANUFACTURING PRACTICES FOR THE EDIBLE INSECTS SECTOR

While insects are a good source of food, it is important not to overstate the benefits without giving due consideration to areas like food safety, which needs thorough investigation. Food safety concerns may vary based on whether insects are collected from the wild or farmed. Further studies on how to safely produce, process, store, and transport insects and insect-based products are needed to successfully facilitate the introduction of such products into the global market. While using food side streams to rear insects would be a good way to incorporate a circular economy approach, thorough food safety risk assessments must be carried out to determine the various safety issues that may arise and affect consumer health. The potential for allergenic risks associated with edible insects needs more research as well.

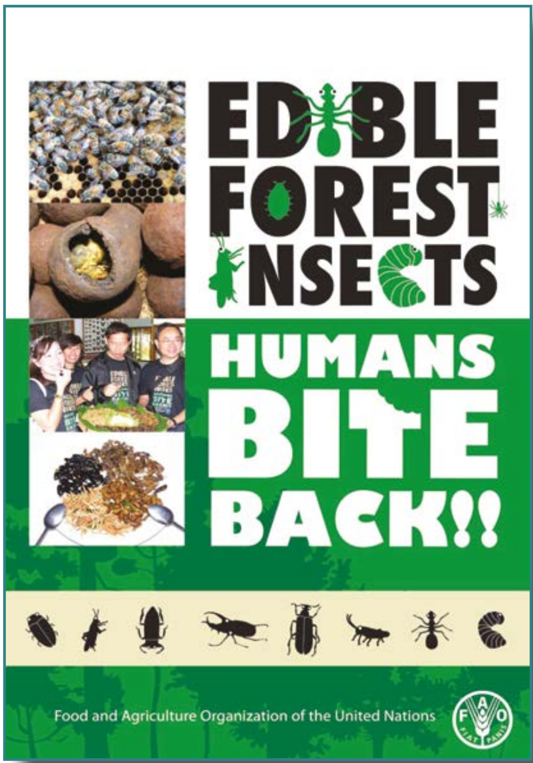
THERE ARE CHALLENGES THAT THE EMERGING INSECTS' SECTOR WILL NEED TO OVERCOME IF IT IS TO EXPAND ITS CONSUMER BASE

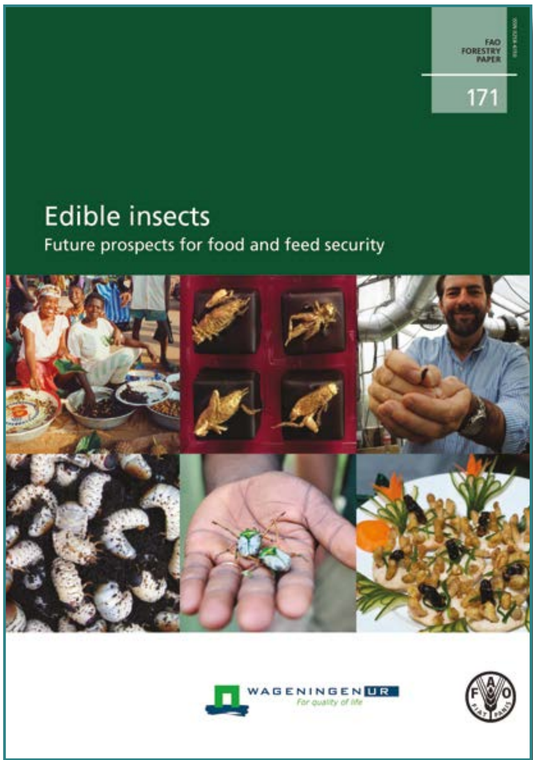
There is a general lack of regulatory frameworks for producing and commercializing insects largely due to various knowledge gaps. Some of these knowledge gaps have been identified in this document. Developing appropriate regulatory frameworks (legislation, standards, and other regulatory instruments) and harmonizing them across national borders would be needed to govern and guide this emerging sector at a national and global level. Upscaling insect production will be necessary if it is to compete with the conventional food and feed sources. There are various challenges associated with this, some of which are covered in this publication. Consumer acceptance of edible insects, mainly in the Western nations, is an area that will require targeted efforts by the insect producers. Deriving and trying different approaches to motivate consumers to accept insects and insect-based food products will be necessary.

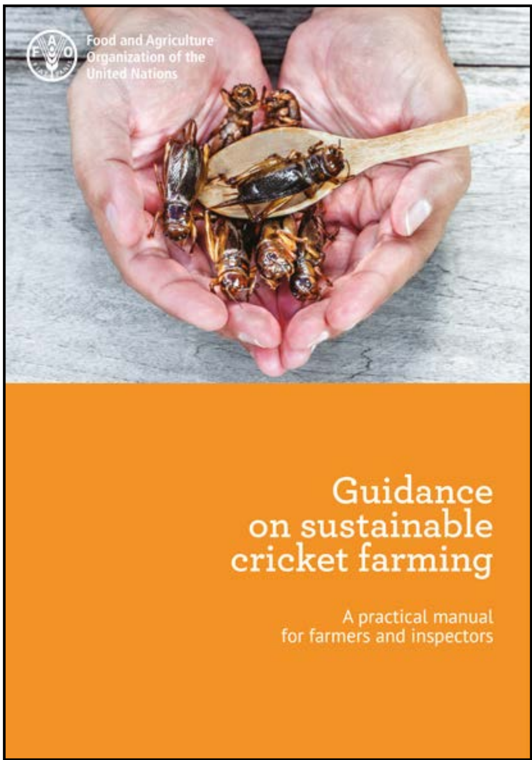
Edible palm weevil larvae served at a local market in Ecuador.

ENHANCING RESEARCH ON KNOWLEDGE GAPS, DEVELOPING APPROPRIATE REGULATORY FRAMEWORKS, AND ENCOURAGING CLOSE COLLABORATION AMONG STAKEHOLDERS WILL FACILITATE ESTABLISHING A MULTIDISCIPLINARY PATHWAY FOR THE SECTOR

The insect farming sector has an opportunity to learn from the livestock industry and cautiously consider how to sustainably integrate insects into our food systems from the very beginning. This includes educating producers on the implications of using agrochemicals in insect production, producing evidence-based policies to regulate the sector, establishing and enforcing good manufacturing practices, fostering close collaboration among all stakeholders involved to build a multidisciplinary platform from the get-go, and investing in research efforts to improve quality standards and advance innovation. As this sector grows, traditional knowledge and practices with respect to collecting, processing, storing, and consuming of insects from various regions must be recognized. Together with scientific knowledge, traditional knowledge can help enhance the sustainability and performance of this emerging sector.







Showcasing some of FAO's previous publications about edible insects.

REFERENCES

Alattar, M., Alattar, F. & Popa, R. 2016. Effects of microaerobic fermentation and black soldier fly larvae food scrap processing residues on the growth of corn plants (*Zea mays*). *Plant Science Today*, 3, pp. 57–62.

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D. & Rounsevell, M.D.A. 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security* 15, pp. 22–32.

All About Feed. 2016. *New Proteins: Insect meal allowance expected in 2020* [online]. [Accessed 13 November 2020]. https://www.allaboutfeed.net/New-Proteins/Articles/2016/12/Insect-meal-allowance-expected-in-2020-68992E/.

Amadi, E.N. & Kiln-Kabari, D.B. 2016. Nutritional Composition and Microbiology of Some Edible Insects Commonly Eaten in Africa, Hurdles and Future Prospects: A Critical Review. *Journal of Food: Microbiology, Safety & Hygiene*, 1, pp. 107.

Anastopoulos, I., Bhatnagar, A., Bikiaris, D. & Kyzas, G. 2017. Chitin Adsorbents for Toxic Metals: A Review. *International Journal of Molecular Sciences*, 18, pp. 114.

ANSES (French Agency for Food, Environmental and Occupational Health and Safety). 2015. *The use of insects as food and feed and the review of scientific knowledge on the health risks related to the consumption of insects.* Maisons-Alfort. 38 pp. (also available at https://www.anses.fr/en/system/files/BIORISK2014sa0153EN.pdf).

Arru, B., Furesi, R., Gasco, L., Madau, F. & Pulina, P. 2019. The Introduction of Insect Meal into Fish Diet: The First Economic Analysis on European Sea Bass Farming. *Sustainability*, 11, pp. 1697.

Bailey, S.E., Olin, T.J., Bricka, R.M. & Adrian, D.D. 1999. A review of potentially low-cost sorbents for heavy metals. *Water Research*, 33, pp. 2469–2479.

Barroso, F.G., De Haro, C., Sánchez-Muros, M.-J., Venegas, E., Martínez-Sánchez, A. & Pérez-Bañón, C. 2014. The potential of various insect species for use as food for fish. *Aquaculture*, 422-423, pp. 193–201.

Bednarska, A.J., Opyd, M., Żurawicz, E. & Laskowski, R. 2015. Regulation of body metal concentrations: toxicokinetics of cadmium and zinc in crickets. *Ecotoxicology and Environmental Safety*, 119, pp. 9–14.

Belluco, S., Halloran, A. & Ricci, A. 2017. New protein sources and food legislation: the case of edible insects and EU law. *Food Security*, 9, pp. 803–814.

Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C.C., Paoletti, M.G. & Ricci, A. 2013. Edible Insects in a food safety and nutritional perspective: a critical review. *Comprehensive Reviews in Food Science and Food Safety*, 12, pp. 296–313.

Berggren, Å., Jansson, A. & Low, M. 2019. Approaching ecological sustainability in the emerging insects-as-food industry. *Trends in Ecology & Evolution*, 34, pp. 132–138.

Bernstein, D.I., Gallagher, J.S. & Leonard Bernstein, I. 1983. Mealworm asthma: clinical and immunologic studies. *Journal of Allergy and Clinical Immunology*, 72, pp. 475–480.

Bessa, L.W., Pieterse, E., Marais, J. & Hoffman, L.C. 2020. Why for feed and not for human consumption? The black soldier fly larvae. *Comprehensive Reviews in Food Science and Food Safety*, 19, pp. 2747–2763.

Bodenheimer, F.S. 1951. *Insects as human food; a chapter of the ecology of man*. The Hague, Dr. W. Junk Publishers.

Bosch, G., Fels-Klerx, H., Rijk, T. & Oonincx, D. 2017. Aflatoxin B1 tolerance and accumulation in black soldier fly larvae (*Hermetia illucens*) and yellow mealworms (*Tenebrio molitor*). *Toxins*, 9, pp. 185.

Boulaiche, W., Hamdi, B. & Trari, M. 2019. Removal of heavy metals by chitin: equilibrium, kinetic and thermodynamic studies. *Applied Water Science*, 9.

Braide, W., Solomon, O., Udegbunam, I., Oguoma, O., Akobondu, C. & Nwaoguikpe, R. 2011. Microbiological quality of an edible caterpillar of an emperor moth, Bunaea alcinoe. *Journal of Ecology and the Natural Environment*, 3, pp. 176–180.

Brandon, A.M., El Abbadi, S.H., Ibekwe, U.A., Cho, Y.-M., Wu, W.-M. & Criddle, C.S. 2020. Fate of hexabromocyclododecane (HBCD), a common flame retardant, in polystyrene-degrading mealworms: elevated HBCD levels in egested polymer but no bioaccumulation. *Environmental Science & Technology*, 54, 364–371.

Brandon, A.M., Gao, S.-H., Tian, R., Ning, D., Yang, S.-S., Zhou, J., Wu, W.-M. & Criddle, C.S. 2018. Biodegradation of polyethylene and plastic mixtures in mealworms (larvae of *Tenebrio molitor*) and effects on the gut microbiome. *Environmental Science & Technology*, 52, pp. 6526–6533.

Brinchmann, B.C., Bayat, M., Brøgger, T., Muttuvelu, D.V., Tjønneland, A. & Sigsgaard, T. 2011. A possible role of chitin in the pathogenesis of asthma and allergy. *Annals of Agriculture and Environmental Medicine,* 11, pp. 7–12.

Broekman, H., Verhoeckx, K.C., Den Hartog Jager, C.F., Kruizinga, A.G., Pronk-Kleinjan, M., Remington, B.C., Bruijnzeel-Koomen, C.A., Houben, G.F. & Knulst, A.C. 2016. Majority of shrimp-allergic patients are allergic to mealworm. *Journal of Allergy and Clinical Immunology*, 137, pp. 1261–1263.

Broekman, H.C.H.P., Knulst, A.C., De Jong, G., Gaspari, M., Den Hartog Jager, C.F., Houben, G.F. & Verhoeckx, K.C.M. 2017a. Is mealworm or shrimp allergy indicative for food allergy to insects? *Molecular Nutrition & Food Research*, 61, 1601061.

Broekman, H.C.H.P., Knulst, A.C., Den Hartog Jager, C.F., van Bilsen, J.H.M., Raymakers, F.M.L., Kruizinga, A.G., Gaspari, M., Gabriele, C., Bruijnzeel-Koomen, C.A.F.M., Houben, G.F. & Verhoeckx, K.C.M. 2017b. Primary respiratory and food allergy to mealworm. *Journal of Allergy and Clinical Immunology*, 140, pp. 600–603.e7.

Bulak, P., Polakowski, C., Nowak, K., Waśko, A., Wiącek, D. & Bieganowski, A. 2018. *Hermetia illucens* as a new and promising species for use in entomoremediation. *Science of The Total Environment*, 633, pp. 912–919.

Camenzuli, L., van Dam, R., De Rijk, T., Andriessen, R., van Schelt, J. & van Der Fels-Klerx, H. 2018. Tolerance and excretion of the mycotoxins aflatoxin B1, zearalenone, deoxynivalenol, and ochratoxin A by *Alphitobius diaperinus* and *Hermetia illucens* from contaminated substrates. *Toxins*, 10, pp. 91.

Caporizzi, R., Derossi, A. & Severini, C. 2019. Cereal-based and insect-enriched printable food: from formulation to postprocessing treatments. Status and perspectives. In Godoi, F.C., Bhandari, B.R., Prakash, S. & Zhang, M. eds. *Fundamentals of 3D food printing and applications*, pp. 93–116. Academic Press.

Cappellozza, S., Saviane, A., Tettamanti, G., Squadrin, M., Vendramin, E., Paolucci, P., Franzetti, E. & Squartini, A. 2011. Identification of *Enterococcus mundtii* as a pathogenic agent involved in the "flacherie" disease in *Bombyx mori* L. larvae reared on artificial diet. *Journal of Invertebrate Pathology*, 106, pp. 386–393.

Cardoso, P., Barton, P.S., Birkhofer, K., Chichorro, F., Deacon, C., Fartmann, T., Fukushima, C.S., Gaigher, R., Habel, J.C., Hallmann, C.A., Hill, M.J., Hochkirch, A., Kwak, M.L., Mammola, S., Ari Noriega, J., Orfinger, A.B., Pedraza, F., Pryke, J.S., Roque, F.O., Settele, J., Simaika, J.P., Stork, N.E., Suhling, F., Vorster, C. & Samways, M.J. 2020. Scientists' warning to humanity on insect extinctions. *Biological Conservation*, 242, pp. 108426.

Cerritos, R. & Cano-Santana, Z. 2008. Harvesting grasshoppers *Sphenarium purpurascens* in Mexico for human consumption: A comparison with insecticidal control for managing pest outbreaks. *Crop Protection*, 27, pp. 473–480.

Chai, J.-Y., Shin, E.-H., Lee, S.-H. & Rim, H.-J. 2009. Foodborne Intestinal Flukes in Southeast Asia. *The Korean Journal of Parasitology*, 47, pp. S69.

Chakravorty, J., Ghosh, S., Megu, K., Jung, C. & Meyer-Rochow, V.B. 2016. Nutritional and anti-nutritional composition of *Oecophylla smaragdina* (Hymenoptera: Formicidae) and *Odontotermes* sp. (Isoptera: Termitidae): Two preferred edible insects of Arunachal Pradesh, India. *Journal of Asia-Pacific Entomology*, 19, pp. 711–720.

Charlotte, L.R.P., Mitsutoshi, U., Shadreck, D., Asako, A., Chisato, T. & Kenichi, N. 2015. The mineral composition of five insects as sold for human consumption in Southern Africa. *African Journal of Biotechnology*, 14, pp. 2443–2448.

Charlton, A.J., Dickinson, M., Wakefield, M.E., Fitches, E., Kenis, M., Han, R., Zhu, F., Kone, N., Grant, M., Devic, E., Bruggeman, G., Prior, R. & Smith, R. 2015. Exploring the chemical safety of fly larvae as a source of protein for animal feed. *Journal of Insects as Food and Feed*, 1, pp. 7–16.

Charrondière, R.U., Stadlmayr, B., Rittenschober, D., Mouille, B., Nilsson, E., Medhammar, E., Olango, T., Eisenwagen, S., Persijn, D., Ebanks, K., Nowak, V., Du, J. & Burlingame, B. 2013. FAO/INFOODS food composition database for biodiversity. *Food Chemistry*, 140, pp. 408–412.

Chia, S.Y., Macharia, J., Diiro, G.M., Kassie, M., Ekesi, S., van Loon, J.J.A., Dicke, M. & Tanga, C.M. 2020. Smallholder farmers' knowledge and willingness to pay for insect-based feeds in Kenya. *PLOS ONE*, 15, e0230552 [online]. [Cited 15 December 2020]. doi.org/10.1371/journal.pone.0230552

Chomchai, S. & Chomchai, C. 2018. Histamine poisoning from insect consumption: an outbreak investigation from Thailand. *Clinical Toxicology*, 56, pp. 126–131.

Costa-Neto, E.M. 2016. Edible insects in Latin America: old challenges, new opportunities. *Journal of Insects as Food and Feed*, 2, pp. 1–2.

Dangles, O. & Casas, J. 2019. Ecosystem services provided by insects for achieving sustainable development goals. *Ecosystem Services*, 35, pp. 109–115.

De Paepe, E., Wauters, J., van Der Borght, M., Claes, J., Huysman, S., Croubels, S. & Vanhaecke, L. 2019. Ultra-high-performance liquid chromatography coupled to quadrupole orbitrap high-resolution mass spectrometry for multi-residue screening of pesticides, (veterinary) drugs and mycotoxins in edible insects. *Food Chemistry*, 293, pp. 187–196.

Defoliart, G.R. 1997. An overview of the role of edible insects in preserving biodiversity. *Ecology of Food and Nutrition*, 36, pp. 109–132.

Defoliart, G.R. 1999. INSECTS AS FOOD: Why the Western Attitude Is Important. *Annual Review of Entomology*, 44, pp. 21–50.

Derrien, C. & Boccuni, A. 2018. Current Status of the Insect Producing Industry in Europe. In Halloran, A., Flore, R., Vantomme, P. & Roos, N. eds. *Edible Insects in Sustainable Food Systems*, pp. 471–479. Springer International Publishing.

Dicke, M. 2018. Insects as feed and the Sustainable Development Goals. *Journal of Insects as Food and Feed*, 4, pp. 147–156.

Dicke, M., Ellenberg, J., Salles, J.F., Jensen, A.B., Lecocq, A., Pijlman, G.P., van Loon, J.J.A. & van Oers, M.M. 2020. Edible insects unlikely to contribute to transmission of coronavirus SARS-CoV-2. *Journal of Insects as Food and Feed*, 6, pp. 333–339.

Diener, S., Zurbrügg, C. & Tockner, K. 2015. Bioaccumulation of heavy metals in the black soldier fly, *Hermetia illucens* and effects on its life cycle. *Journal of Insects as Food and Feed*, 1, pp. 261–270.

Dobermann, D., Swift, J.A. & Field, L.M. 2017. Opportunities and hurdles of edible insects for food and feed. *Nutrition Bulletin*, 42, pp. 293–308.

Dube, M. 2020. Dry spell kills Botswana's 'edible diamonds', hitting rural communities. *Voice of America*, 6 February 2020. (also available at https://www.voanews.com/africa/dry-spell-kills-botswanas-edible-diamonds-hitting-rural-communities).

Durst, P.B. & Hanboonsong, Y. 2015. Small-scale production of edible insects for enhanced food security and rural livelihoods: experience from Thailand and Lao People's Democratic Republic. *Journal of Insects as Food and Feed*, 1, pp. 25–31.

EC (European Commission). 2002. Council Directive (EC) 2002/32/EC of 7 May 2002 on undesireable substances in animal feed. *Official Journal of the European Union*, L140: pp. 12–21.

EFSA CONTAM Panel (EFSA Panel on Contaminants in the Food Chain). 2012. Scientific opinion on mineral oil hydrocarbons in food. *EFSA Journal*, 10, 2704. doi:10.2903/j.efsa.2012.2704.

EFSA NDA Panel (EFSA Panel on Dietetic Products, Nutrition and Allergies). 2016a. Guidance on the preparation and presentation of an application for authorisation of a novel food in the context of Regulation (EU) 2015/2283. *EFSA Journal*, 14, 4594. doi:10.2903/j.efsa.2016.4594.

EFSA NDA Panel (EFSA Panel on Dietetic Products, Nutrition and Allergies). 2016b. Guidance on the preparation and presentation of the notification and application for authorisation of traditional foods from third countries in the context of Regulation (EU) 2015/2283. *EFSA Journal*, 14, 4590. doi:10.2903/j.efsa.2016.4590.

EFSA NDA Panel (EFSA Panel on Nutrition, Novel Foods and Food Allergens). 2021. Scientific opinion on the safety of yellow mealworm (*Tenebrio molitor* larva) as a novel food pursuant to Regulation (EU) 2015/2283. *EFSA Journal*, 19, 6343. doi:10.2903/j.efsa.2021.6343

EFSA Scientific Committee. 2015. Scientific opinion on a risk profile related to production and consumtion of insects as food and feed. *EFSA Journal*, 13, 4257. doi:10.2903/j.efsa.2015.4257.

Ekop, E.A., Udoh, A.I. & Akpan, P.E. 2010. Proximate and anti-nutrient composition of four edible insects in Akwa Ibom State, Nigeria. *World African Journal of Pharmacy and Pharmacology*, 3, pp. 51–57.

Einstein-Curtis, A. 2019. CFIA: Increasing interest in insect feed ingredients prompt guidance check. *Feed Navigator*, 21 June 2019. (also available at https://www.feednavigator.com/Article/2019/06/21/CFIA-Interest-in-insect-feed-ingredients-prompts-guidance-check).

Ewuim, S.C. 2013. Entomoremediation – A novel in-situ bioremediation approach. *Animal Research International*, 10, pp. 1681–1684.

FAO. 2007. Edible insects: eating worms and protecting parks in Namibia. NWFP-Digest L3. (also available at http://www.fao.org/forestry/49997/en/#P72_7934).

FAO. 2013. *Edible insects. Future prospects for food and feed security*. FAO Forestry Paper 171. Rome, FAO. pp. 201. (also available at http://www.fao.org/3/i3253e/i3253e.pdf).

FAO. 2020. *Southwest Asia. Desert locust crisis appeal, May – December 2020. Rapid response and scaled-up action.* Rome, FAO. pp. 20. (http://www.fao.org/3/ca9250en/CA9250EN.pdf).

INFOODS. 2013. *FAO/INFOODS Food Composition Database for Biodiversity Version 2.1 – BioFoodComp2.1.* Rome, FAO. pp. 33 (also available at http://www.fao.org/3/i3560e/i3560e.pdf).

FAO & OECD. 2018. *Food security and nutrition: challenges for agriculture and the hidden potential of soil*. A report to the G20 Agriculture Deputies. Rome, FAO, pp. 40 (also available at http://www.fao.org/3/CA0917EN/ca0917en.pdf).

FAO & WHO. 1991. *Protein quality evaluation*. Report of the Joint FAO/WHO Expert Consultation 4 – 8 December 1989, Bethesda, Maryland, United States of America. FAO Food and Nutrition Paper No. 51, Rome, FAO. pp. 66 (also available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1021.9259&rep=rep1&type=pdf).

FAO & WHO. 2019. *Hazards associated with animal feed*. Report of the Joint FAO/WHO Expert Meeting 12 – 15 May 2015, FAO headquarters, Rome, Italy. FAO Animal Production and Health Report, No. 13, pp. 286 (also available at http://www.fao.org/3/ca6825en/CA6825EN.pdf).

Fasolato, L., Cardazzo, B., Carraro, L., Fontana, F., Novelli, E. & Balzan, S. 2018. Edible processed insects from e-commerce: Food safety with a focus on the *Bacillus cereus* group. *Food Microbiology*, 76, pp. 296–303.

Fernandez-Cassi, X., Supeanu, A., Jansson, A., Boqvist, S. & Vagsholm, I. 2018. Novel foods: a risk profile for the house cricket (*Acheta domesticus*). *EFSA Journal*, 16, e16082 [online]. [Cited 25 November 2020]. doi.org/10.2903/j.efsa.2018.e16082.

Ferrer Llagostera, P., Kallas, Z., Reig, L. & Amores De Gea, D. 2019. The use of insect meal as a sustainable feeding alternative in aquaculture: Current situation, Spanish consumers' perceptions and willingness to pay. *Journal of Cleaner Production*, 229, pp. 10–21.

Finke, M.D., & Oonincx, D.G.A.B. 2014. Insects as food for insectivores. In Morales-Ramos, J. & Shapiro-Ilan, D. eds. *Mass production of beneficial organisms*, pp. 583–616. San Diego: Academic.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpernter, S.R., Chaplin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. & Snyder, P.K. Global consequences of land use. *Science*, 309, pp. 570–574.

Fowles, T.M. & Nansen, C. 2020. Insect-based bioconversion: value from food waste. In Närvänen, E., Mesiranta, N., Mattila, M. & Heikkinen, A. eds. *Food Waste Management*. pp. 321–346. Palgrave Macmillian, Cham.

Freye, H.B., Esch, R.E., Litwin, C.M. & Sorkin, L. 1996. Anaphylaxis to the ingestion and inhalation of *Tenebrio molitor* (mealworm) and Zophobas morio (superworm). *Allergy and Asthma Proceedings*, 17, pp. 215–219.

Gahukar, R.T. 2016. Edible Insects Farming: Efficiency and Impact on Family Livelihood, Food Security, and Environment Compared With Livestock and Crops. In Dossey. A.T., Morales-Ramos, J.A. & Guadalupe Rojas, M. eds. *Insects as Sustainable Food Ingredients. Production, Processing and Food Applications*. pp. 85–111. Academic Press.

Gałęcki, R. & Sokół, R. 2019. A parasitological evaluation of edible insects and their role in the transmission of parasitic diseases to humans and animals. *PLOS ONE*, 14, e0219303 [online]. [Cited 5 December 2020]. doi.org/10.1371/journal.pone.0219303.

Gao, Y., Chen, J., Wang, H., Liu, C., Lv, X., Li, J. & Guo, B. 2013. Enantiomerization and Enantioselective Bioaccumulation of Benalaxyl in Tenebrio molitor Larvae from Wheat Bran. *Journal of Agricultural and Food Chemistry*, 61, pp. 9045–9051.

Gao, Y., Wang, H., Qin, F., Xu, P., Lv, X., Li, J. & Guo, B. 2014. Enantiomerization and enantioselective bioaccumulation of metalaxyl in *Tenebrio molitor* larvae. *Chirality*, 26, pp. 88–94.

Garino, C., Zagon, J. & Braeuning, A. 2019. Insects in food and feed – allergenicity risk assessment and analytical detection. *EFSA Journal*, 17, e170907. doi.org/10.2903/j.efsa.2019.e170907.

Garofalo, C., Milanović, V., Cardinali, F., Aquilanti, L., Clementi, F. & Osimani, A. 2019. Current knowledge on the microbiota of edible insects intended for human consumption: A state-of-the-art review. *Food Research International*, 125, pp. 108527.

Garofalo, C., Osimani, A., Milanović, V., Taccari, M., Cardinali, F., Aquilanti, L., Riolo, P., Ruschioni, S., Isidoro, N. & Clementi, F. 2017. The microbiota of marketed processed edible insects as revealed by high-throughput sequencing. *Food Microbiology*, 62, pp. 15–22.

Gautreau, M., Restuccia, M., Senser, K. & Weisberg, S.N. 2017. Familial anaphylaxis after silkworm ingestion. *Prehospital Emergency Care*, 21, pp. 83–85.

Gaylor, M.O., Harvey, E. & Hale, R.C. 2012. House crickets can accumulate polybrominated diphenyl ethers (PBDEs) directly from polyurethane foam common in consumer products. *Chemosphere*, 86, pp. 500–505.

Gere, A., Székely, G., Kovács, S., Kókai, Z. & Sipos, L. 2017. Readiness to adopt insects in Hungary: A case study. *Food Quality and Preference*, 59, pp. 81–86.

Globe Newswire. 2016. New Insect Protein Gains Approval for Use in Animal Feed: Regulatory Approval First of Its Kind in Canada. 20 July 2016 [online]. *Globe Newswire* [Accessed 17 November 2020]. https://www.globenewswire.com/news-release/2016/07/20/1040286/0/en/New-Insect-Protein-Gains-Approval-for-Use-in-Animal-Feed-Regulatory-Approval-First-of-Its-Kind-in-Canada.html.

Globe Newswire. 2019. $7.95 Billion Edible Insects Market: Global Forecast to 2030. Research and Markets 1 April 2019 [online]. *Globe Newswire* [Accessed 30 December 2020]. https://www.globenewswire.com/news-release/2019/04/01/1790970/0/en/7-95-Billion-Edible-Insects-Market-Global-Forecast-to-2030.html.

Globe Newswire. 2020. Global $1.39 Bn Insect Feed Market, 2024: Insights Into Growth Trends & Opportunties. 9 March 2020. *Globe Newswire* [Accessed 23 December 2020]. https://www.globenewswire.com/news-release/2020/03/09/1996978/0/en/Global-1-39-Bn-Insect-Feed-Market-2024-Insights-Into-Growth-Trends-Opportunities.html.

Gmuer, A., Nuessli Guth, J., Hartmann, C. & Siegrist, M. 2016. Effects of the degree of processing of insect ingredients in snacks on expected emotional experiences and willingness to eat. *Food Quality and Preference*, 54, pp. 117–127.

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

Gortari, M.C. & Hours, R.A. 2013. Biotechnological processes for chitin recovery out of crustacean waste: a mini review. Electronic Journal of Biotechnology, 16. doi.org/10.2225/vol16-issue3-fulltext-10.

Gounot, A.-M. 1986. Psychrophillic and psychrotrophic microorganisms. *Experientia*, 42, pp. 1192–1197.

Grabowski, N.T. & Klein, G. 2017. Bacteria encountered in raw insect, spider, scorpion, and centipede taxa including edible species, and their significance from the food hygiene point of view. *Trends in Food Science & Technology*, 63, pp. 80–90.

Grabowski, N.T., Tchibozo, S., Abdulmawjood, A., Acheuk, F., M'Saad Guerfali, M., Sayed, W.A.A. & Plötz, M. 2020. Edible insects in Africa in terms of food, wildlife resource, and pest management legislation. *Foods*, 9, pp. 502.

Graczyk, T.K., Knight, R. & Tamang, L. 2005. Mechanical transmission of human protozoan parasites by insects. *Clinical Microbiology Reviews*, 18, pp. 128–132.

Greenfield, R., Akala, N. & van Der Bank, F.H. 2014. Heavy metal concentrations in two populations of mopane worms (*Imbrasia belina*) in the Kruger National Park pose a potential human health risk, *Contamination and Toxicology*, 93, pp. 316–321.

Gullan, P.J. & Cranston, P.S. 2014. *The insects: An outline of entomology*. 5th edition. Wiley-Blackwell, UK

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D. & De Kroon, H. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE*, 12, e0185809 [online]. [Cited 17 November 2020]. doi.org/10.1371/journal.pone.0185809.

Halloran, A., Hanboonsong, Y., Roos, N. & Bruun, S. 2017a. Life cycle assessment of cricket farming in north-eastern Thailand. *Journal of Cleaner Production*, 156, pp. 83–94.

Halloran, A., Roos, N., Eilenberg, J., Cerutti, A. & Bruun, S. 2016. Life cycle assessment of edible insects for food protein: a review. *Agronomy for Sustainable Development*, 36.

Halloran, A., Roos, N. & Hanboonsong, Y. 2017b. Cricket farming as a livelihood strategy in Thailand. *The Geographical Journal*, 183, pp. 112–124.

Halloran, A., Vantomme, P., Hanboonsong, Y. & Ekesi, S. 2015. Regulating edible insects: the challenge of addressing food security, nature conservation, and the erosion of traditional food culture. *Food Security*, 7, pp. 739–746.

Hanboonsong, Y. & Durst, P. 2020. Guidance on sustainable cricket farming – A pratical manual. Bangkok, FAO. pp. 84. (also available at https://doi.org/10.4060/cb2446en).

Hanboonsong, Y., Jamjanya, T. & Durst, P. 2013. Six-legged livestock: edible insect farming, collection and marketing in Thailand. Bangkok, FAO. pp. 69. (also available at http://www.fao.org/3/a-i3246e.pdf).

Handley, M.A., Hall, C., Sanford, E., Diaz, E., Gonzalez-Mendez, E., Drace, K., Wilson, R., Villalobos, M. & Croughan, M. 2007. Globalization, binational communities, and imported food risks: results of an outbreak investigation of lead poisoning in Monterey County, California. *American Journal of Public Health*, 97, pp. 900–906.

Harsányi, E., Juhász, C., Kovács, E., Huzsval, L., Pintér, R., Fekete, G., Varga, Z.I., Aleksza, L. & Gyuricza, C. 2020. Evaluation of organic wastes as substrates for rearing *Zophobas morio*, *Tenebrio molitor*, and *Acheta domesticus* larvae as laternative feed supplements. *Insects*, 11, pp. 604.

Hartmann, C., Shi, J., Giusto, A. & Siegrist, M., 2015. The psychology of eating insects: A cross-cultural comparison between Germany and China. *Food Quality and Preference*, 44, pp. 148–156.

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J.Y., van Meijl, H., van Zeist, W.-J., Wiebe, K. & Witzke, P. 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, 8, pp. 699–703.

Hirose, E., Panizzi, A.R. & Cattelan, A.J. 2006. Potential use of antibiotic to improve performance of laboratory-reared *Nezara viridula* (L.) (Heteroptera: Pentatomidae). *Neotropical Entomology,* 35, pp. 279-281.

Hogan, G.R. & Razniak, H.G. 1991. Selenium-induced mortality and tissue distribution studies in *Tenebrio molitor* (Coleoptera: Tenebrionidae). *Environmental Entomology*, 20, pp. 790–794.

Houben, D., Daoulas, G., Faucon, M.-P. & Dulaurent, A.-M. 2020. Potential use of mealworm frass as a fertilizer: Impact on crop growth and soil properties. *Scientific Reports*, 10.

Houbraken, M., Spranghers, T., De Clercq, P., Cooreman-Algoed, M., Couchement, T., De Clercq, G., Verbeke, S. & Spanoghe, P. 2016. Pesticide contamination of *Tenebrio molitor* (Coleoptera: Tenebrionidae) for human consumption. *Food Chemistry*, 201, pp. 264–269.

House, J. 2016. Consumer acceptance of insect-based foods in the Netherlands: Academic and commercial implications. *Appetite*, 107, pp. 47–58.

Hussein, M., Pillai, V.V., Goddard, J.M., Park, H.G., Kothapalli, K.S., Ross, D.A., Ketterings, Q.M., Brenna, J.T., Milstein, M.B., Marquis, H., Johnson, P.A., Nyrop, J.P. & Selvaraj, V. 2017. Sustainable production of housefly (*Musca domestica*) larvae as a protein-rich feed ingredient by utilizing cattle manure. *PLoS ONE*, 12, e0171708 [online]. [Cited 12 October 2020]. doi.org/10.1371/journal.pone.0171708.

IARC (International Agency for Research on Cancer). 1993. Some naturally occurring substances: Food items and constituents, heterocyclic aromatic amines and mycotoxins. *IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans*, Vol. 56. Lyon, IARC. pp. 599 (also available at https://publications.iarc.fr/74).

Imathiu, S. 2020. Benefits and food safety concerns associated with consumption of edible insects. *NFS Journal*, 18, pp. 1–11.

Ipema, A.F., Bokkers, E.A.M., Gerrits, W.J.J., Kemp, B. & Bolhuis, E. 2020a. Long-term access to live black soldier fly larvae (*Hermetia illucens*) stimulates activity and reduces fearfulness of broilers, without affecting health. *Scientific Report*s, 10.

Ipema, A.F., Gerrits, W.J.J., Bokkers, E.A.M., Kemp, B. & Bolhuis, E. 2020b. Provisioning of live black soldier fly larvae (*Hermetia illucens*) benefits broiler activity and leg health in a frequency- and dose-dependent manner. *Applied Animal Behaviour Science*, 230, pp. 105082.

IPIFF (International Platform for Insects as Food and Feed). 2019a. *Regulation (EU) 2015/2283 on novel foods*. Briefing paper on the provisions relevant to the commercialization of insect-based products intended for human consumption in the EU. Brussels, IPIFF (also available at https://ipiff.org/wp-content/uploads/2019/08/ipiff_briefing_update_03.pdf).

IPIFF. 2019b. *Guidance: the provision of food information to consumers. Edible insect-based products*. Brussels, IPIFF (also available at https://ipiff.org/wp-content/uploads/2019/09/FIC-doc.pdf).

IPIFF. 2020. *Edible insects on the European market.* Factsheet. Brussels, IPIFF (also available at https://ipiff.org/wp-content/uploads/2020/06/10-06-2020-IPIFF-edible-insects-market-factsheet.pdf).

Ites, S., Smetana, S., Toepfl, S. & Heinz, V. 2020. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. *Journal of Cleaner Production*, 248, 119248.

Ji, K.-M., Zhan, Z.-K., Chen, J.-J. & Liu, Z.-G. 2008. Anaphylactic shock caused by silkworm pupa consumption in China. *Allergy*, 63, pp. 1407–1408.

Joly, G. & Nikiema, J. 2019. *Global experiences on waste processing with black soldier fly (Hermetia illucens): from technology to business.* Colombo Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). Resource Recovery and Reuse Series No. 16. pp. 62 (also available at http://www.iwmi.cgiar.org/Publications/wle/rrr/resource_recovery_and_reuse-series_16.pdf).

Jongema, Y. 2017. *List of Edible Insect Species of the World*. Laboratory of Entomology, Wageningen University, The Netherlands (also available at https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm).

Kim, T.-K., Yong, H.I., Kim, Y.-B., Kim, H.-W. & Choi, Y.-S. 2019. Edible insects as a protein source: A review of public perception, processing technology, and research trends. *Food Science of Animal Resources*, 39, pp. 521–540.

Klein, A. 2019. Would you eat insects to help save the planet? These companies are betting yes. *The Washington Post*. 9 January, 2019 (also available at https://www.washingtonpost.com/lifestyle/2019/01/09/would-you-toss-roasted-insects-into-your-meal-this-health-app-is-betting-yes/).

Klunder, H.C., Wolkers-Rooijackers, J., Korpela, J.M. & Nout, M.J.R. 2012. Microbiological aspects of processing and storage of edible insects. *Food Control*, 26, pp. 628–631.

Knightingale, K.W. & Ayim, E.N. 1980. Outbreak of botulism in Kenya after ingestion of white ants. *The British Medical Journal*, 281, pp. 1682–1683.

Kobayashi, M., Agui, N., Sasaki, T., Saito, N., Tamura, K., Suzuki, K. & Watanabe, H. 1999. Houseflies: not simple mechanical vectors of enterohemorrhagic *Escherichia coli* O157:H7. *The American Journal of Tropical Medicine and Hygiene*, 61, pp. 625–629.

Koh, D.W.-S., Ang, B.Y.-X., Yeo, J.Y., Xing, Z. & Gan, S.K.-E. 2020. Plastic agriculture using worms: Augmenting polystyrene consumption and using frass for plant growth towards a zero-waste circular economy. *bioRxiv* (preprint server). doi.org/10.1101/2020.05.29.123521

Kooh, P., Ververis, E., Tesson, V., Boué, G. & Federighi, M. 2019. Entomophagy and public health: A review of microbiological hazards. *Health*, 11, pp. 1272–1290.

Kozanayi, W. & Frost, P. 2002. *Marketing of mopane worm in southern Zimbabwe*. Mopane worm market survey in southern Zimbabwe. Institute of Environmental Studies, University of Zimbabwe. pp. 17.

La Barbera, F., Verneau, F., Amato, M. & Grunert, K. 2018. Understanding Westerners' disgust for the eating of insects: The role of food neophobia and implicit associations. *Food Quality and Preference*, 64, pp. 120–125.

Lähteenmäki-Uutela, A., Grmelová, N., Hénault-Ethier, L., Deschamps, M.-H., Vandenberg, G.W., Zhao, A., Zhang, Y., Yang, B. & Nemane, V. 2017. Insects as food and feed: Laws of the European Union, United States, Canada, Mexico, Australia, and China. *European Food and Feed Law Review*, 12, pp. 22–36.

Law, Y. & Wein, L. 2018. Reversing the nutrient drain through urban insect farming - opportunities and challenges. *AIMS Bioengineering*, 5, pp. 226–237.

Lee, H.L., Chandrawathani, P., Wong, W.Y., Tharam, S. & Lim, W.Y. 1995. A case of human enteric myiasis due to larvae of *Hermetia illucens* (Family: Stratiomyiadae): first report in Malaysia. *Malaysian Journal of Pathology*, 17, pp. 109–111.

Lee, C.G., Da Silva, C.A., Lee, J-.Y., Hartl, D. & Elias, J.A. 2008. Chitin regulation of immune responses: an old molecule with new roles. *Current Opinion in Immunology*, 20, pp. 684–689.

Leni, G., Tedeschi, T., Faccini, A., Pratesi, F., Folli, C., Puxeddu, I., Migliorini, P., Gianotten, N., Jacobs, J., Depraetere, S., Caligiani, A. & Sforza, S. 2020. Shotgun proteomics, in-silico evaluation and immunoblotting assays for allergenicity assessment of lesser mealworm, black soldier fly and their protein hydrolysates. *Scientific Reports*, 10.

Li, L., Xie, B., Dong, C., Wang, M. & Liu, H. 2016. Can closed artificial ecosystem have an impact on insect microbial community? A case study of yellow mealworm (*Tenebrio molitor* L.). *Ecological Engineering*, 86, pp. 183–189.

Lister, B.C. & Garcia, A. 2018. Climate-driven declines in arthropod abundance restructure a rainforest food web. *Proceedings of the National Academy of Sciences*, 115, pp. E10397–E10406.

Liu, C., Tian Lv, X., Zhu, W.X., Yang Qu, H., Gao, Y.X., Guo, B.Y. & Wang, H.L. 2013. Enantioselective bioaccumulation of diniconazole in *Tenebrio molitor* larvae. *Chirality*, 25, pp. 917–922.

Liu, Y., Lai, Q., Göker, M., Meier-Kolthoff, J.P., Wang, M., Sun, Y., Wang, L. & Shao, Z. 2015. Genomic insights into the taxonomic status of the *Bacillus cereus* group. *Scientific Reports*, 5.

Lombardi, A., Vecchio, R., Borrello, M., Caracciolo, F. & Cembalo, L. 2019. Willingness to pay for insect-based food: The role of information and carrier. *Food Quality and Preference*, 72, pp. 177–187.

Lv, X., Liu, C., Li, Y., Gao, Y., Guo, B., Wang, H. & Li, J. 2013. Bioaccumulation and excretion of enantiomers of myclobutanil in *Tenebrio molitor* larvae through dietary exposure. *Chirality*, 25, pp. 890–896.

Lv, X., Liu, C., Li, Y., Gao, Y., Wang, H., Li, J. & Guo, B. 2014. Stereoselectivity in bioaccumulation and excretion of epoxiconazole by mealworm beetle (*Tenebrio molitor*) larvae. *Ecotoxicology and Environmental Safety*, 107, pp. 71–76.

Makhado, R., Potgieter, M., Timberlake, J. & Gumbo, D. 2014. A review of the significance of mopane products to rural people's livelihoods in southern Africa. *Transactions of the Royal Society of South Africa*, 69, pp. 117–122.

Martínez, S., Borrajo, R., Franco, I. & Carballo, J. 2007. Effect of environmental parameters on growth kinetics of *Bacillus cereus* (ATCC 7004) after mild heat treatment. *International Journal of Food Microbiology*, 117, pp. 223–227.

Meyer-Rochow, V. 1975. Can insects help to ease the problem of world food shortage. *Search*, 6, pp. 261–262.

Miech, P., Berggren, Å., Lindberg, J.E., Chhay, T., Khieu, B. & Jansson, A. 2016. Growth and survival of reared Cambodian field crickets (*Teleogryllus testaceus*) fed weeds, agricultural and food industry by-products. *Journal of Insects as Food and Feed*, 2, pp. 285–292.

Miglietta, P., De Leo, F., Ruberti, M. & Massari, S. 2015. Mealworms for food: A water footprint perspective. *Water*, 7, pp. 6190–6203.

Miranda, C.D., Cammack, J.A. & Tomberlin, J.K. 2019. Life-history traits of house fly, *Musca domestica* L. (Diptera: Muscidae), reared on three manure types. *Journal of Insects as Food and Feed*, 6, pp, 81–91.

Morales-Ramos, J.A., Rojas, M.G., Dossey, A.T. & Berhow, M. 2020. Self-selection of food ingredients and agricultural by-products by the house cricket, *Acheta domesticus* (Orthoptera: Gryllidae): A holistic approach to develop optimized diets. *PLOS ONE*, 15, e0227400 [online]. [Cited 4 October 2020]. doi.org/10.1371/journal.pone.0227400.

Moyo, A., Bimbo, F., Adeyoyin, K., Nnaemeka, A., Oluwatoyin, G. & Oladeji, A. 2014. Seasonal ataxia: a case report of a disappearing disease. *African Health Sciences*, 14, pp. 769.

Murefu, T.R., Macheka, L., Musundire, R. & Manditsera, F.A. 2019. Safety of wild harvested and reared edible insects: A review. *Food Control*, 101, pp. 209–224.

Mpuchane, S., Gashe, B.A., Allotey, J., Siame, B., Teferra, G. & Ditlhogo, M. 2000. Quality deterioration of phane, the edible caterpillar of an emperor moth *Imbrasia belina*. *Food control*, 11, pp. 453–458.

Mpuchane, S. F., Taligoola, H. K., & Gashe, B. A. 1996. Fungi associated with *Imbrasia belina* an edible caterpillar. *Botswana Notes and Records*, 28, pp. 193–198.

Musundire, R., Zvidzai, C.J., Chidewe, C., Ngadze, R.T., Macheka, L., Manditsera, F.A., Mubaiwa, J. & Masheka, A. 2016. Aflatoxin contamination detected in nutrient and anti-oxidant rich edible stink bug stored in recycled grain containers. *PLOS ONE*, 11, e0145914 [online]. [Cited 11 December 2020]. doi.org/10.1371/journal.pone.0145914.

Musundire, R., Zvidzai, J.C. & Chidewe, C. 2014. Bio-active compounds composition in edible stinkbugs consumed in south-eastern districts of Zimbabwe. *International Journal of Biology*, 6.

Nakagaki, B.J. & Defoliart, G.R. 1991. Comparison of diets for mass-rearing *Acheta domesticus* (Orthoptera: Gryllidae) as a novelty food, and comparison of food conversion efficiency with values reported for livestock. *Journal of Economic Entomology*, 84, pp. 891–896.

Niermans, K., Woyzichovski, J., Kröncke, N., Benning, R. & Maul, R. 2019. Feeding study for the mycotoxin zearalenone in yellow mealworm (*Tenebrio molitor*) larvae—investigation of biological impact and metabolic conversion. *Mycotoxin Research*, 35, pp. 231–242.

Nishimune, T., Watanabe, Y., Okazaki, H. & Akai, H. 2000. Thiamin Is decomposed due to *Anaphe* spp. Entomophagy in seasonal ataxia patients in Nigeria. *The Journal of Nutrition*, 130, pp. 1625–1628.

Niassy, S., Ekesi, S., Hendriks, S.K. & Haller-Barker, A. 2018. Legislation for the use of insects as food and feed in the South African context. In Halloran, A., Flore, R., Vantomme, P. & Roos, N., eds. *Edible insects in sustainable food systems*. pp. 457–470. Springer, Cham.

Nowak, V., Persijn, D., Rittenschober, D. & Charrondière, U.R. 2016. Review of food composition data for edible insects. *Food Chemistry*, 193, pp. 39–46.

Nukmal, N., Umar, S., Amanda, S.P. & Kanedi, M. 2018. Effect of styrofoam waste feeds on the growth, development and fecundity of mealworms (*Tenebrio molitor*). *OnLine Journal of Biological Sciences*, 18, pp. 24–28.

NVWA (The Netherlands Food and Consumer Product Safety Authority). 2014. Advisory report on the risks associated with the consumption of mass-reared insects. Utrecht, NVWA (also available at https://zenodo.org/record/439001#.X_e_59hKhPZ).

O'Neal, S.L. & Zheng, W., 2015. Manganese toxicity upon overexposure: a decade in review. *Current Environmental Health Reports*, 2, pp. 315–328.

Oibiopka, F.I., Akanya, H.O., Jigam, A.A., Saidu, A.N. & Egwim, E.C. 2018. Protein quality of four indigenous edible insect species in Nigeria. *Food Science and Human Wellness*, 7, pp. 175–183.

Okezie, O.A., Kgomotso, K.K. & Letswiti, M.M. 2010. Mopane worm allergy in a 36-year-old woman: a case report. *Journal of Medical Case Reports*, 4, pp. 42.

Oonincx, D.G.A.B. & De Boer, I.J.M. 2012. Environmental impact of the production of mealworms as a Protein Source for Humans – A Life Cycle Assessment. *PLOS ONE*, 7, e51145 [online]. [Cited 2 November 2020]. doi.org/10.1371/journal.pone.0051145.

Oonincx, D.G.A.B., van Huis, A. & van Loon, J.J.A. 2015. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. *Journal of Insects as Food and Feed*, 1, pp. 131–139.

Oonincx, D.G.A.B., van Itterbeeck, J., Heetkamp, M.J.W., van Den Brand, H., van Loon, J.J.A. & van Huis, A. 2010. An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLOS ONE*, 5, e14445 [online]. [Cited 11 October 2020]. doi.org/10.1371/journal.pone.0014445.

Osimani, A., Garofalo, C., Milanović, V., Taccari, M., Cardinali, F., Aquilanti, L., Pasquini, M., Mozzon, M., Raffaelli, N., Ruschioni, S., Rioli, P., Isidoro, N. & Clementi, F. 2017a. Insight into the proximate composition and microbial diversitiy of edible insects marketed in the European Union. *European Food Research and Technology*, 243, pp. 1157–1171.

Osimani, A., Cardinali, F., Aquilanti, L., Garofalo, C., Roncolini, A., Milanović, V., Pasquini, M., Tavoletti, S. & Clementi, F. 2017b. Occurrence of transferable antibiotic resistances in commercialized ready-to-eat mealworms (*Tenebrio molitor* L.). *International Journal of Food Microbiology*, 263, pp. 38–46.

Osimani, A., Milanović, V., Cardinali, F., Garofalo, C., Clementi, F., Ruschioni, S., Riolo, P., Isidoro, N., Loreto, N., Galarini, R., Moretti, S., Petruzzelli, A., Micci, E., Tonucci, F. & Aquilanti, L. 2018a. Distribution of transferable antibiotic resistance genes in laboratory-reared edible mealworms (*Tenebrio molitor* L.). *Frontiers in Microbiology*, 9.

Osimani, A., Milanović, V., Garofalo, C., Cardinali, F., Roncolini, A., Sabbatini, R., De Filippis, F., Ercolini, D., Gabucci, C., Petruzzelli, A., Tonucci, F., Clementi, F. & Aquilanti, L. 2018b. Revealing the microbiota of marketed edible insects through PCR-DGGE, metagenomic sequencing and real-time PCR. *International Journal of Food Microbiology*, 276, pp. 54–62.

Owoeye, N. 2020. Grubbing bugs: Can we get over the 'ick' factor? *Food Safety News,* 1 June 2020 (also available at https://www.foodsafetynews.com/2020/06/grubbing-bugs-can-we-get-over-the-ick-factor/).

Pali-Schöll, I., Meinlschmidt, P., Larenas-Linnemann, D., Purschke, B., Hofstetter, G., Rodríguez-Monroy, F.A., Einhorn, L., Mothes-Luksch, N., Jensen-Jarolim, E. & Jäger, H. 2019. Edible insects: Cross-recognition of IgE from crustacean- and house dust mite allergic patients, and reduction of allergenicity by food processing. *World Allergy Organization Journal*, 12, 100006.

Paine, J.M., McKee, M.J. & Ryan, M.E. 1993. Toxicity and bioaccumulation of soil PCBs in crickets: comparison of laboratory and field studies. *Environmental Toxicity and Chemistry*, 12, pp. 2097–2103.

Park, M., Boys, E.L., Yan, M., Bryant, K., Cameron, B., Desai, A., Thomas, P.S. & Tedla, N.T. 2014. Hypersensitivity pneumonitis caused by house cricket, *Acheta domesticus*. *Journal of Clinical & Cellular Immunology*, 5, 1000248.

Parodi, A., Leip, A., De Boer, I.J.M., Slegers, P.M., Ziegler, F., Temme, E.H.M., Herrero, M., Tuomisto, H., Valin, H., van Middelaar, C.E., van Loon, J.J.A. & van Zanten, H.H.E. 2018. The potential of future foods for sustainable and healthy diets. *Nature Sustainability*, 1, pp. 782–789.

Parry, N.J., Pieterse, E. & Weldon, C.W. 2020. Stocking rate and organic waste type affect development of three *Chrysomya* species and *Lucilia sericata* (Diptera: Calliphoridae): Implications for bioconversion. *Journal of Applied Entomology*, 144, pp. 94–108.

Payne, C.L.R., Scarborough, P., Rayner, M. & Nonaka, K. 2016. Are edible insects more or less 'healthy' than commonly consumed meats? A comparison using two nutrient profiling models developed to combat over- and undernutrition. *European Journal of Clinical Nutrition*, 70, pp. 285–291.

Payne, C.L.R., Umemura, M., Dube, S., Azuma, A., Takenaka, C. & Nonaka, K. 2015. The mineral composition of five insects as sold for human consumption in Southern Africa. *African Journal of Biotechnology*, 14, pp. 2443–2448.

Peng, Y.-SC, Mussen, E., Fong, A., Montgue, M.A. & Tyler, T. 1992. Effects of chlortetracycline of honey bee worker larvae reared in vitro. *Journal of Invertebrate Pathology*, 60, pp. 127–133.

Pener, M.P. 2014. Allergy to locusts and acridid grasshoppers: a review. *Journal of Orthoptera Research*, 23, pp. 59–67.

Phiriyangkul, P., Srinroch, C., Srisomsap, C., Chokchaichamnankit, D. & Punyarit, P. 2015. Effect of food thermal processing on allergenicity proteins in Bombay locust (*Patanga Succincta*). *ETP International Journal of Food Engineering*, 1.

Pinotti, L., Giromini, C., Ottoboni, M., Tretola, M. & Marchis, D, 2019. Review: Insects and former foodstuffs for upgrading food waste biomasses/streams to feed ingredients for farm animals. *Animal*, 13, pp. 1365–1375.

Pleissner, D. & Rumpold, B.A. 2018. Utilization of organic residues using heterotrophic microalgae and insects. *Waste Management*, 72, pp. 227–239.

Poma, G., Cuykx, M., Amato, E., Calaprice, C., Focant, J.F. & Covaci, A. 2017. Evaluation of hazardous chemicals in edible insects and insect-based food intended for human consumption. *Food and Chemical Toxicology*, 100, pp. 70–79.

Poma, G., Yin, S., Tang, B., Fujii, Y., Cuykx, M. & Covaci, A. 2019. Occurrence of selected organic contaminants in edible insects and assessment of their chemical safety. *Environmental Health Perspectives*, 127, 127009.

PROteINSECT. 2016. Final report summary – PROTEINSECT. *Enabling the Exploitation of Insects as a Sustainable Source of Protein for Animal Feed and Human Nutrition*. (also available at https://cordis.europa.eu/project/id/312084/reporting).

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

Raheem, D., Carrascosa, C., Oluwole, O.B., Nieuwland, M., Saraiva, A., Millán, R. & Raposo, A. 2019. Traditional consumption of and rearing edible insects in Africa, Asia and Europe. *Critical Reviews in Food Science and Nutrition*, 59, pp. 2169–2188.

Ramos-Elorduy, J. 2006. Threatened edible insects in Hidalgo, Mexico and some measures to preserve them. *Journal of Ethnobiology and Ethnomedicine*, 2, pp. 51.

Ramos-Elorduy, J. 2009. Anthropo-entomophagy: cultures, evolution and sustainability. *Entomological Research*, 39, pp. 271–288.

Ramos-Elorduy, J., González, E.A., Hernández, A.R. & Pino, J.M. 2002. Use of *Tenebrio molitor* (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. *Journal of Economic Entomology*, 95, pp. 214–220.

Reese, G., Ayuso, R. & Lehrer, S.B. 1999. Tropomyosin: an invertebrate pan–allergen. *International Archives of Allergy and Immunology*, 119, pp. 247–258.

Reverberi, M. 2020. Edible insects: cricket farming and processing as an emerging market. *Journal of Insects as Food and Feed*, 6, pp. 211–220.

Ribeiro, J.C., Cunha, L.M., Sousa-Pinto, B. & Fonseca, J. 2018. Allergic risks of consuming edible insects: A systematic review. *Molecular Nutrition & Food Research*, 62, 1700030.

Roffeis, M., Muys, B., Almeida, J., Mathijs, E., Achten, W.M.J., Pastor, B., Velásquez, Y., Martinez-Sanchez, A.I. & Rojo, S. 2015. Pig manure treatment with housefly (*Musca domestica*) rearing – an environmental life cycle assessment. *Journal of Insects as Food and Feed*, 1, pp. 195–214.

Roncolini, A., Cardinali, F., Aquilanti, L., Milanović, V., Garofalo, C., Sabbatini, R., Abaker, M.S.S., Pandolfi, M., Pasquini, M., Tavoletti, S., Clementi, F. & Osimani, A. 2019. Investigating antibiotic resistance genes in marketed ready-to-eat Small crickets (*Acheta domesticus*). *Journal of Food Science*, 84, pp. 3222–3232.

Rumpold, B.A. & Schlüter, O.K. 2013. Nutritional composition and safety aspects of edible insects. *Molecular Nutrition & Food Research*, 57, pp. 802–823.

Saeed, T. 1993. Analysis of residual pesticides present in edible locusts captured in Kuwait. *The Arab Gulf Journal of Scientific Research*, 11, pp. 1–5.

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S. & Savastano, D. 2017. Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using *Hermetia illucens*. *Journal of Cleaner Production*, 140, pp. 890–905.

Schabel H.G. 2010. Forest insects as food: a global review. *In* Durst, P.B, Johnson, D.V., Leslie, R.N. & Shono, K., eds. *Edible Forest Insect: Humans Bite Back*. Proceedings of a workshop on Asia-Pacific resources and their potential for development. Bangkok, FAO.

Schlüter, O., Rumpold, B., Holzhauser, T., Roth, A., Vogel, R.F., Quasigroch, W., Vogel, S., Heinz, V., Jäger, H., Bandick, N., Kulling, S., Knorr, D., Steinberg, P. & Engel, K.-H. 2017. Safety aspects of the production of foods and food ingredients from insects. *Molecular Nutrition & Food Research*, 61, 1600520.

Schrögel, P. & Wätjen, W. 2019. Insects for food and feed-safety aspects related to mycotoxins and metals. *Foods*, 8, pp. 288.

Seibold, S., Gossner, M.M., Simons, N.K., Blüthgen, N., Müller, J., Ambarlı, D., Ammer, C., Bauhus, J., Fischer, M., Habel, J.C., Linsenmair, K.E., Nauss, T., Penone, C., Prati, D., Schall, P., Schulze, E.-D., Vogt, J., Wöllauer, S. & Weisser, W.W. 2019. Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature*, 574, pp. 671–674.

Schneider, J., ed. 2009. *Environmental biology of insect rearing. Principles and procedures for rearing high quality insects*. pp. 97–120. Mississippi State University, U.S.A.

Shantibala, T., Lokeshwari, R.K. & Debaraj, H. 2014. Nutritional and antinutritional composition of the five species of aquatic edible insects consumed in Manipur, India. *Journal of Insect Science*, 14, pp. 14–14.

Siozios, S., Massa, A., Parr, C.L., Verspoor, R.L. & Hurst, G.D.D. 2020. DNA barcoding reveals incorrect labeling of insects sold as food in the UK. *PeerJ*, 8, e8496 [online]. [Cited 3 October 2020]. doi.org/10.7717/peerj.8496

Skrivervik, E. 2020. Insects' contribution to the bioeconomy and the reduction of food waste. *Heliyon*, 6, e03934 [online]. [Cited 18 November 2020]. doi.org/10.1016/j.heliyon.2020.e03934.

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

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

Sogari, G., Menozzi, D., Hartmann, C. & Mora, C. 2019. How to measure consumers acceptance towards edible insects? – A scoping review about methodological approaches. In Sogari,G., Mora,C. & Menozzi, D. eds. *Edible insects in the Food Sector*, pp. 27–44. Springer, Cham.

Srinroch, C., Srisomsap, C., Chokchaichamnankit, D., Punyarit, P. & Phiriyangkul, P. 2015. Identification of novel allergen in edible insect, Gryllus bimaculatus and its cross-reactivity with Macrobrachium spp. allergens. *Food Chemistry*, 184, pp. 160–166.

Stoops, J., Crauwels, S., Waud, M., Claes, J., Lievens, B. & van Campenhout, L. 2016. Microbial community assessment of mealworm larvae (*Tenebrio molitor*) and grasshoppers (*Locusta migratoria migratorioides*) sold for human consumption. *Food Microbiology*, 53, pp. 122–127.

Surendra, K.C., Olivier, R., Tomberlin, J.K., Jha, R. & Khanal, S.K. 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. *Renewable Energy*, 98, pp. 197–202.

Surendra, K.C., Tomberlin, J.K., van Huis, A., Cammack, J.A., Heckmann, L.-H.L. & Khanal, S.K. 2020. Rethinking organic wastes bioconversion: Evaluating the potential of the black soldier fly (*Hermetia illucens* (L.)) (Diptera: Stratiomyidae) (BSF). *Waste Management*, 117, pp. 58–80.

Szelei, J., Woodring, J., Goettel, M.S., Duke, G., Jousset, F.-X., Liu, K.Y., Zadori, Z., Li, Y., Styer, E., Boucias, D.G., Kleespies, R.G., Bergoin, M. & Tijssen, P. 2011. Susceptibility of North-American and European crickets to Acheta domesticus densovirus (AdDNV) and associated epizootics. *Journal of Invertebrate Pathology*, 106, pp. 394–399.

Tao, J. & Li, Y.O. 2018. Edible insects as a means to address global malnutrition and food insecurity issues. *Food Quality and Safety*, 2, pp. 17–26.

Tebele, M. 2020. Drought hit SADC witnesses decline in mopane worms. *The Southern Times*, 14 February 2020. (also available at https://southerntimesafrica.com/site/news/drought-hit-sadc-witnesses-decline-in-mopane-worms).

Thomas, B. 2013. Sustainable harvesting and trading of mopane worms (*Imbrasia belina*) in Northern Namibia: an experience from the Uukwaluudhi area. *International Journal of Environmental Studies*, 70, pp. 494–502.

UN (United Nations). 2019. *World Population Prospects 2019: highlights* (ST/ESA/SER.A/423). Department of Economic and Social Affairs, Population Division. New York, UN. 46 pp. (also available at https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf).

UNEP (United Nations Environment Programme). 2021. *Food Waste Index Report.* Nairobi. 100 pp. (also available at https://wedocs.unep.org/bitstream/handle/20.500.11822/35280/FoodWaste.pdf).

van Broekhoven, S., Gutierrez, J.M., De Rijk, T.C., De Nijs, W.C.M. & van Loon, J.J.A. 2017. Degradation and excretion of the *Fusarium* toxin deoxynivalenol by an edible insect, the yellow mealworm (*Tenebrio molitor* L.). *World Mycotoxin Journal*, 10, pp. 163–169.

van Broekhoven, S., Oonincx, D.G.A.B., van Huis, A. & van Loon, J.J.A. 2015. Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. *Journal of Insect Physiology*, 73, pp. 1–10.

van der Fels-Klerx, H.J., Camenzuli, L., Belluco, S., Meijer, N. & Ricci, A. 2018. Food safety issues related to uses of insects for feeds and foods. *Comprehensive Reviews in Food Science and Food Safety*, 17, pp. 1172–1183.

van der Fels-Klerx, H.J., Camenzuli, L., van Der Lee, M.K. & Oonincx, D.G.A.B. 2016. Uptake of cadmium, lead and arsenic by *Tenebrio molitor* and *Hermetia illucens* from contaminated substrates. *PLOS ONE*, 11, e0166186 [online]. [Cited 10 October 2020]. doi.org/10.1371/journal.pone.0166186.

van der Fels-Klerx, H.J., Meijer, N., Nijkamp, M.M., Schmitt, E. & van Loon, J. 2020. Chemical food safety of using former foodstuffs for rearing black soldier fly larvae (*Hermetia illucens*) for feed and food use. *Journal of Insects as Food and Feed*, 6, pp. 475–488.

van Huis. A. 2003. Insects as food in sub-Saharan Africa. *Insect Science and its Application*, 23, pp. 163–185.

van Huis, A. 2013. Potential of Insects as Food and Feed in Assuring Food Security. *Annual Review of Entomology*, 58, pp. 563–583.

van Huis, A. 2015. Edible insects contributing to food security? *Agriculture & Food Security*, 4.

van Huis, A. 2016. Edible insects are the future? *Proceedings of the Nutrition Society*, 75, pp. 294–305.

van Huis, A. 2020. Insects as food and feed, a new emerging agricultural sector: a review. *Journal of Insects as Food and Feed*, 6, pp. 27–44.

van Huis, A. & Oonincx, D.G.A.B. 2017. The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development*, 37.

van Strien, A.J., van Swaay, C.A.M.,van Strien-Van Liempt, W.T.F.H., Poot, M.J.M. & Wallisdevries, M.F. 2019. Over a century of data reveal more than 80% decline in butterflies in the Netherlands. *Biological Conservation*, 234, pp. 116–122.

van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G. & De Boer, I.J.M. 2015. From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. *Journal of Cleaner Production*, 102, pp. 362–369.

Vandeweyer, D., Crauwels, S., Lievens, B. & van Campenhout, L. 2017a. Microbial counts of mealworm larvae (*Tenebrio molitor*) and crickets (*Acheta domesticus* and *Gryllodes sigillatus*) from different rearing companies and different production batches. *International Journal of Food Microbiology*, 242, pp. 13–18.

Vandeweyer, D., Lenaerts, S., Callens, A. & van Campenhout, L. 2017b. Effect of blanching followed by refrigerated storage or industrial microwave drying on the microbial load of yellow mealworm larvae (*Tenebrio molitor*). *Food Control*, 71, pp. 311–314.

Vandeweyer, D., Lievens, B. & van Campenhout, L. 2020. Identification of bacterial endospores and targeted detection of foodborne viruses in industrially reared insects for food. *Nature Food*, 1, pp. 511–516.

Vandeweyer, D., Milanović, V., Garofalo, C., Osimani, A., Clementi, F., van Campenhout, L. & Aquilanti, L. 2019. Real-time PCR detection and quantification of selected transferable antibiotic resistance genes in fresh edible insects from Belgium and the Netherlands. *International Journal of Food Microbiology*, 290, pp. 288–295.

Veldkamp, T. & Bosch, G. 2015. Insects: A protein-rich feed ingredients in pig and poultry diets. *Animal Frontiers*, 2, pp. 45–50.

Verbeke, W. 2015. Profiling consumers who are ready to adopt insects as a meat substitute in a Western society. *Food Quality and Preference*, 39, pp. 147–155.

Verheyen, G.R., Theunis, M., Vreysen, S., Naessens, T., Noyens, I., Ooms, T., Goossens, S., Pieters, L., Foubert, K. & van Miert, S. 2020. Glycine-acyl surfactants prepared from black soldier fly fat, coconut oil and palm kernel oil. *Current Green Chemistry*, 7, pp. 239–248.

Verhoeckx, K.C.M., van Broekhoven, S., Den Hartog-Jager, C.F., Gaspari, M., De Jong, G.A.H., Wichers, H.J., van Hoffen, E., Houben, G.F. & Knulst, A.C. 2014. House dust mite (Der p 10) and crustacean allergic patients may react to food containing yellow mealworm proteins. *Food and Chemical Toxicology*, 65, pp. 364–373.

Verneau, F., La Barbera, F., Kolle, S., Amato, M., Del Giudice, T. & Grunert, K. 2016. The effect of communication and implicit associations on consuming insects: An experiment in Denmark and Italy. *Appetite*, 106, pp. 30–36.

Verspoor, R.L., Soglo, M., Adeoti, R., Djouaka, R., Edwards, S., Fristedt, R., Langton, M., Moriana, R., Osborne, M., Parr, C.L., Powell, K., Hurst, G.D.D. & Landberg, R. 2020. Mineral analysis reveals extreme manganese concentrations in wild harvested and commercially available edible termites. *Scientific Reports*, 10.

Vijver, M., Jager, T., Posthuma, L. & Peijnenburg, W. 2003. Metal uptake from soils and soil–sediment mixtures by larvae of *Tenebrio molitor* (L.) (Coleoptera). *Ecotoxicology and Environmental Safety*, 54, pp. 277–289.

Wales, A.D., Carrique-Mas, J.J., Rankin, M., Bell, B., Thind, B.B. & Davies, R.H. 2010. Review of the carriage of zoonotic bacteria by arthropods, with special reference to *Salmonella* in mites, flies and litter beetles. *Zoonoses and Public Health*, 57, pp. 299–314.

Walia, K., Kapoor, A. & Farber, J.M. 2018. Qualitative risk assessment of cricket powder to be used to treat undernutrition in infants and children in Cambodia. *Food Control*, 92, pp. 169–182.

Wang, Y.-S. & Shelomi, M. 2017. Review of black soldier fly (*Hermetia illucens*) as animal feed and human food. *Foods*, 6, pp. 91.

Weissman, D., Gray, D., Pham, H. & Tussen, P. 2012. Billions and billions sold: Pet-feeder crickets (Orthoptera: Gryllidae), commercial cricket farms, an epizootic densovirus, and government regulations make for a potential disaster. *Zootaxa*, 3504: pp. 67–88.

Westerhout, J., Krone, T., Snippe, A., Babé, L., McClain, S., Ladics, G.S., Houben, G.F. & Verhoeckx, K.C.M. 2019. Allergenicity prediction of novel and modified proteins: Not a mission impossible! Development of a random Forest allergenicity prediction model. *Regulatory Toxicology and Pharmacology*, 107, 104422.

Wynants, E., Crauwels, S., Lievens, B., Luca, S., Claes, J., Borremans, A., Bruyninckx, L. & van Campenhout, L. 2017. Effect of post-harvest starvation and rinsing on the microbial numbers and the bacterial community composition of mealworm larvae (*Tenebrio molitor*). *Innovative Food Science & Emerging Technologies*, 42, pp. 8–15.

Xiao, X., Mazza, L., Yu, Y., Cai, M., Zheng, L., Tomberlin, J.K., Yu, J., van Huis, A., Yu, Z., Fasulo, S. & Zhang, J. 2018. Efficient co-conversion process of chicken manure into protein feed and organic fertilizer by *Hermetia illucens* L. (Diptera: Stratiomyidae) larvae and functional bacteria. *Journal of Environmental Management*, 217, pp. 668–676.

Yang, Y., Yang, J., Wu, W.-M., Zhao, J., Song, Y., Gao, L., Yang, R. & Jiang, L. 2015a. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 1. Chemical and physical characterization and isotopic tests. *Environmental Science & Technology*, 49, pp. 12080–12086.

Yang, Y., Yang, J., Wu, W.-M., Zhao, J., Song, Y., Gao, L., Yang, R. & Jiang, L. 2015b. Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 2. Role of gut microorganisms. *Environmental Science & Technology*, 49, pp. 12087–12093.

Yen, A.L. 2009. Entomophagy and insect conservation: some thoughts for digestion. *Journal of Insect Conservation*, 13, pp. 667–670.

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

Yi, C., He, Q., Wang, L. & Kuang, R. 2010. The utilization of insect-resources in Chinese rural area. *Journal of Agricultural Sciences,* 2, pp. 146–154.

Zhang, X., Tang, H., Chen, G., Qiao, L., Li, J., Liu, B., Liu, Z., Li, M. & Liu, X. 2019. Growth performance and nutritional profile of mealworms reared on corn stover, soybean meal, and distillers' grains. *European Food Research and Technology*, 245, pp. 2631–2640.

Zhang, Z.-S., Lu, X.-G., Wang, Q.-C. & Zheng, D.-M. 2009. Mercury, cadmium and lead biogeochemistry in the soil–plant–insect system in Huludao City. *Bulletin of Environmental Contamination and Toxicology*, 83, pp. 255–259.

Zhou, J. & Han, D. 2006. Safety evaluation of protein of silkworm (*Antheraea pernyi*) pupae. *Food and Chemical Toxicology*, 44, pp. 1123–1130.

Zurek, L. & Ghosh, A. 2014. Insects represent a link between food animal farms and the urban environment for antibiotic resistance traits. *Applied and Environmental Microbiology*, 80, pp. 3562–3567.

Looking at edible insects from a food safety perspective

Challenges and opportunities for the sector

For centuries, insects have been consumed as a part of the normal diet in a number of regions worldwide. Traditionally edible insects have been collected from the wild, but in recent years mass rearing systems are being developed in many countries to meet the growing demand for food sources that are both nutritious and environmentally sustainable.

To fully realize the various benefits that the edible insects' sector can bring, it is important to identify and address all knowledge gaps, one of which is thorough investigation of the food safety issues that may affect the health of consumers. This publication describes some of the key food safety concerns that could be associated with edible insects. The hazards considered are biological (bacteria, viruses, fungi) and chemical (mycotoxins, heavy metals, pesticides). The allergenic potential of edible insects is also explored.

Despite the longstanding use of insects as a food source, there are very few national laws for insect production and consumption, and limited harmonization of regulations across national borders that address trade. This publication provides a brief overview of the regulatory frameworks that govern the farming and use of insects, mainly as food, in various regions. In addition, a few other challenges for the sector, such as research gaps and scaling up production, are identified and discussed.

This publication is meant for food safety professionals, policymakers, researchers, insect producers, as well as consumers.

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