REVIEW

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Opportunities and hurdles of edible insects for food and feed

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Abstract

Entomophagy, the consumption of insects, is promoted as an alternative sustainable source of protein for humans and animals. Seminal literature highlights predominantly the benefits, but with limited empirical support and evaluation. We highlight the historical significance of entomophagy by humans and key opportunities and hurdles identified by research to date, paying particular attention to research gaps. It is known that insects present a nutritional opportunity, being generally high in protein and key micronutrients, but it is unclear how their nutritional quality is influenced by what they are fed. Research indicates that, in ideal conditions, insects have a smaller environmental impact than more traditional Western forms of animal protein; less known is how to scale up insect production while maintaining these environmental benefits. Studies overall show that insects could make valuable economic and nutritional contributions to the food or feed systems, but there are no clear regulations in place to bring insects into such supply systems. Future research needs to examine how the nutritional value of insects can be managed systematically, establish clear processing and storage methodology, define rearing practices and implement regulations with regard to food and feed safety. Each of these aspects should be considered within the specifics of concrete supply and value chains, depending on whether insects are intended for food or for feed, to ensure insects are a sound economic, nutritional and sustainable protein alternative – not just a more expensive version of poultry for food, or soya for feed.

Keywords: edible insects, entomophagy, environment, microlivestock, nutrition

Introduction

Entomophagy, the eating of insects, is not a new phenomenon for humans, with archaeological evidence demonstrating that humans have evolved as an entomophagous species (Sutton 1995; Raubenheimer & Rothman 2011). More recently, for several hundreds of years, humans have been making use of a range of insects as a food source, which is naturally high in protein and micronutrients. In parts of Central Africa, at times, up to 50% of dietary protein comes from insects, and their market value is higher than many alternative sources of animal protein (Paoletti & Dreon 2005; Raubenheimer & Rothman 2011). It has been estimated that entomophagy is practiced in at least 113 countries with over 2000 documented edible

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insect species (Jongema 2017), and the United Nations has recommended the practice as a potential solution to the shortage of world food supplies (van Huis 2013).

Whether the wider adoption of entomophagy could help alleviate growing pressure on the environment from food production, and reduce malnutrition in both developed and developing countries, is a topic of extensive debate. This narrative review aims to highlight some of the opportunities and hurdles associated with entomophagy with respect to malnutrition and food security. The paper will explore the history, culture and customs surrounding the collection and eating of insects; the main nutritional and environmental benefits of entomophagy; and the barriers to the widespread implementation of entomophagy and the steps necessary to counter them. It is intended as a narrative review and as such is not wholly exhaustive of the literature. Rather, it provides a general overview of the state of research on edible insects and current challenges due to the lack of research.

History of insect consumption by humans

Insect species that have become the most commonly consumed are popular due to their size and availability (Bukkens 1997). Insects need to be large enough to make the effort of catching them worthwhile and easy to locate, preferably in predictably large quantities. Thus, popular insects species for consumption fall into the following categories: beetles (*Coleoptera*, 31%); caterpillars (*Lepidoptera*, 18%); bees, wasps and ants (*Hymenoptera*, 14%); grasshoppers, locusts and crickets (*Orthoptera*, 13%); cicadas, leafhoppers, planthoppers, scale insects and true bugs (*Hemiptera*, 10%); termites (*Isoptera*, 3%); dragonflies (*Odonata*, 3%); and flies (*Diptera*, 2%) (Jongema 2017). Insects are consumed at various life-stages and with numerous methods of preparation including raw, fried, boiled, roasted or ground.

In Thailand, for example, 150 different insect species, mostly wild-harvested, are consumed and are a vital staple in the diet (Yhoung-Aree 2010). Entomophagy has also been shown to be a successful method of crop pest control. In 1978, a locust (*Patanga succincta*) outbreak in Thailand resulted in a government campaign to promote the locust's edibility. They became such a popular snack that they are now no longer a crop pest, and their market value means that some farmers now grow crops specifically to feed them (Hanboonsong 2010). An increasing demand for insects as food in Thailand has resulted in a shift from wild collection to the development of mass-rearing facilities, with crickets being the most commonly reared species by individual farmers for whom they provide a valuable source of additional income (Hanboonsong 2010). Similarly, in Kenya and Burkina Faso, there is a rich history of consuming insects, the most popular in Kenya being palm weevil (*Rhynchophrus Phoenicis*) larvae, which are both wild-harvested and semi-cultivated by the chopping down of raffia trees (Kelemu *et al.* 2016). In Burkina Faso, the most commonly consumed insect is the Shea tree caterpillar (*Cirina butyrospermi*), which is considered a pest to the tree plantations grown for the production of shea butter (Anvo *et al.* 2016). The larvae are usually boiled in water and then fried in butter for immediate use or boiled and sun-dried to be sold in the market.

Native human populations in the majority of Africa and Asia, and in large parts of South America, consume various species of insects in a multitude of dishes. However, until recently, the consumption of insects was generally decreasing, partly due to the spread of Western views of insects as a source of fear and disgust, particularly in the context of food (Looy *et al.* 2014). Insects can be seen as a 'starvation food', to be eaten only in times of extreme food shortage (Kinyuru *et al.* 2011; Looy *et al.* 2014). Individuals engaging in entomophagy have been considered as 'rural', 'barbarian' or engaging in 'primitive peoples' practice' (Megido & Sablon 2014; Verbeke 2015). Thus, the negative portrayal of entomophagy by the media and failure to embrace this practice by Westerners and the media has resulted in a decline in insect consumption, with negative health consequences for communities that relied on the nutrition that insects provided (Hanboonsong *et al.* 2013; Verbeke 2015). However, new data suggest that in certain countries, such as Thailand and Laos, the demand for insects is on the rise (Durst & Hanboonsong 2015). These changing attitudes may be due, at least in part, to the increased acceptance that consumption of insects does not only occur in developing countries in times of starvation (Kinyuru *et al.* 2011).

There are many examples of insects being eaten as part of everyday diets. For example, in Japan, insects form part of the traditional diet (Bukkens 1997), with 55 edible species documented in 1919. Although these numbers have dropped, due to environmental and societal changes, there are still a handful of species eaten today, often as delicacy/luxury food items (Nonaka 2010). Wasps are the chosen delicacy in Japan and deeply entrenched in the food culture, with an annual festival celebrating their consumption during which individuals compete to see who has the biggest wasp nest, either wild-harvested or cultivated. Communities come together to celebrate the wasp harvest, exchange knowledge on collection and cultivation methods and eat various wasp delicacies (Nonaka 2010). Farmers also continue to make efforts to improve on wasp husbandry methods, which are often unsuccessful and costly, indicating that enjoyment and tradition are the primary motivators for the keeping of wasps (Payne & Evans 2017).

Opportunities

Nutrition

Insects are a source of energy, protein, fat, minerals and vitamins (Rumpold & Schlüter 2013a), with the energy content being on a par with other fresh meat sources (per fresh weight); the exception being pork due to its high fat content (Rumpold & Schlüter 2013a). Mean estimates show energy levels to be around 400–500 kcal per 100 g of dry matter, making it comparable with other protein sources (Payne 2016).

Macronutrients

Levels of protein, fat and energy vary across insect species and also within species depending on what the insects have fed on, stage of development, sex and environmental factors (Bukkens 1997; Ramos-Elorduy *et al.* 2002; Finke & Oonincx 2014). However, general ranges have been estimated as shown in Table 1.

Protein is a significant component of edible insects, comprising between 30% and 65% of the total dry matter. The quality of protein is determined by both the amino acid composition and the digestibility of the protein, expressed as a percentage of that of an 'ideal' protein (Belluco 2013). Between 46% and 96% of all amino acids are present in insect protein, although there are limited amounts of tryptophan and lysine (Bukkens 1997; Ramos-Elorduy *et al.* 1997), and digestibility is estimated to be between 77% and 98% for most species (Ramos-Elorduy *et al.* 1997). The suitability of insect protein for human nutrition is yet to be assessed, but studies with juvenile rats have demonstrated that crickets (*Acheta domesticus*) offer a superior source of protein when compared to a plant source (soy protein) (Belluco 2013). Human trials of insect consumption remain a significant research gap, and definitive recommendations regarding insects as nutritionally suitable for humans currently cannot be made.

Table 1 Protein, fat and energy content of some insects. Data from Rumpold & Schlüter (2013a). Specific species were selected as examples if they deviated significantly from the average, or are one of the most popularly consumed species. If there was more than one entry for a specific species, the average was calculated

	Protein (% dry matter)	Fat (% dry matter)	Energy (kcal/100 g)
Coleoptera (adult beetles, larvae)	40.69	33.4	490.3
Rhynchophorus phoenicis (palm weevil larvae)	32.86	36.86	478.87
Tenebrio molitor (mealworm larvae)	48.35	38.51	557.12
Diptera (flies)	49.48	22.75	409.78
Hemiptera (true bugs)	48.33	30.26	478.99
Hymenoptera (ants, bees)	46.47	25.09	484.45
Oecophylla smaragdina (weaver ant)	53.46	13.46	
Isoptera (termites)	35.34	32.74	
Lepidoptera (butterflies, moths)	45.38	27.66	508.89
Bombyx mori (silkworm larvae)	61.8	8.81	389.6
Cirina forda (shea caterpillar)	47.48	11.5	359
Galleria mellonella (waxworm larvae)	38.01	56.65	650.13
Samia cynthia ricinii (ailanthus silkworm pupae)	54.7	25.6	463.63
Odonata (dragonflies, damselflies)	55.23	19.83	431.33
Orthoptera (crickets, grasshoppers, locusts)	61.23	13.41	426.25
Acheta domesticus (house cricket adult)	65.04	22.96	455.19
Schistocerca sp.	61.05	17	427
Sphenarium purpuracens (chapulin adult)	61.33	11.7	404.22
Ruspolia differens (brown longhorn grasshopper)	44.3	46.2	

After protein, fat is the next main component of insects. The unsaturated fatty acid profile is similar to that of poultry and white fish but contains more polyunsaturated fatty acids (PUFAs) than either poultry or red meat (Rumpold & Schlüter 2013a). Omega-3 fatty acids, eicosapentaenoic acid (EPA) (C20:5) and docosahexaenoic acid (DHA) (C22:6) being the primary types, are essential for normal cellular functioning and must be supplied by the diet. Insects contain little to no traces of EPA and DHA but do contain linoleic acid (C18:2) and occasionally linolenic acid (C18:3), which humans can synthesise to make arachidonic acid (C20:4) and EPA (Rumpold & Schlüter 2013a; Calder 2017). It must be noted that the fat profiles of insects are highly dependent on their feedstuff. For example, a study has shown that levels of EPA and DHA can be increased in black soldier flies by feeding them fish offal (St-Hilaire *et al.* 2007). More research is needed to draw clear conclusions on the availability of specific fats in insects.

Overall fat content is also highly variable among insects, ranging from 7 to 77 g/100 g of dry weight, with larvae generally having a higher overall content than adults (Ramos-Elorduy *et al.* 1997). Insect larvae and some soft-bodied adult insects, such as termites, have the highest levels of fat, and insects with a hard exoskeleton, such as crickets and grasshoppers, are at the lower end (Bukkens 1997).

Micronutrients

Although micronutrient levels vary greatly across insect species, some species do have consistently higher levels of certain micronutrients. Table 2 summarises the average levels of minerals and vitamins in a range of commonly consumed insect species. A large variation is often seen within a single species due to environmental factors and contaminants, particularly metal, acquired during processing.

Iron has been shown to range from 18 to 1562 mg/100 g dry matter across insect species, with low levels in ants, mid-levels in termites and the highest levels in crickets (Christensen 2006). Metal contaminants may account for some of the reported variation in levels of iron. Although iron levels in insects are high, especially when compared to plant-based food sources generally consumed in place of meat, no research has identified the type of iron found in insects. ‘Haem’ iron, present in animals (with a blood circulatory systems and haemoglobin), is more bioavailable and absorbed more uniformly in the human body than the ‘non-haem’ iron found in plants (Kongkachuichai & Napatthalung 2002; Hurrell & Egli 2010). Insects do have a circulatory system, but this does not involve haemoglobin and so the availability of their iron is unknown, although it has been suggested to have a bioavailability more similar to that of the iron found in meat rather than plants. For example, one study examined the bioavailability of iron in maize-field grasshopper (*Sphenarium purpurascens)*, black crickets (*Gryllus bimaculatus*), mealworms (*Tenebrio molitor*) and buffalo worms (*Alphitobius diaperinus)*. Buffalo worms and sirloin meat were found to have the highest levels of iron bioavailability, with buffalo worms slightly higher than sirloin meat, while the other insects displayed a mid-range of iron bioavailability between the highest and lowest samples (whole wheat) tested (Latunde-Dada & Yang 2016). It should be noted these *in vitro* studies of a Caco-2 cell model and no human or animal trials have been conducted to date.

Zinc, calcium and vitamin A have all been found in insects, but data on the quantities present are limited. Crickets have been reported to contain zinc in the range of 8-25 mg/100 g dry matter (Christensen 2006) and ants, termites and crickets to contain calcium in the range of 33–341 mg/100 g dry matter, with crickets having the highest levels. Vitamin A has been found to range from 3 to 273 μg/100 g dry matter across insect species (Christensen 2006).

Table 2 Mineral and vitamin A content in popularly consumed insect species. All minerals in mg/100 g dry matter except vitamin A (μg/100 g dry matter). Data from Rumpold and Schlüter (2013a)

Species	Calcium	Potassium	Magnesium	Phosphorus	Sodium	Iron	Zinc	Manganese	Copper	Vitamin A
Rhynchophorus phoenicis (African palm weevil larvae)	131.05	1617	82.7	518.5	48.4	22.75	21.15	2.15	1.6	11.25
Tenebrio molitor (mealworm larvae)	45.77	828.28	215.89	722.74	133.16	5.46	12.53	1.14	1.62	
Oecophylla smaragdina (weaver ant)	63.85	749	96.05	726.5	225	65.4	13.5	7.68	1.52	
Agro (termites)	132					161	14.3			
Bombyx mori (silkworm larvae)	102.31	1826.59	287.86	1369.94	274.57	9.54	17.75	2.49	2.08	273.99
Cirina forda Westwood (shea caterpillar)	17.48	1100.91	34.72	480.92	130.39	23.93	6.44	7		2.99
Galleria mellonella (waxworm larvae)	59.28	532.53	83.07	834.94	39.76	6.57	7	0.32	0.62	4.5
Samia ricinii (silkworm pupae)	72.2		182.5	577		23.7	7.13	2.58	1.78	
Acheta domesticus (house cricket adult)	171.07	1126.62	94.71	832.9	435.06	8.75	20.22	3.35	1.43	24.33
Sphenarium purpuracens (chapulin adult)	112	377	424		609	18	42			
Ruspolia differens (brown longhorn grasshopper)	24.5	259.7	33.1	121	229.7	13	12.4	2.5	0.5	280

Overall, the nutritional status of insects is highly variable, depending on different species, diets and life-stages. Additionally, little is known about the digestibility and availability of nutrients from insects for humans or for animals.

Environmental considerations

The environmental impact of food production is increasingly being brought to the forefront of sustainability debates, particularly surrounding the reduction of carbon dioxide (CO_2) emissions. However, there are two other important environmental factors often ignored: water and land use. It is predicted that by 2025, at least 1.8 million people will be living in regions with inadequate freshwater supplies and a further two-thirds of the global population will be in areas under pressure from dwindling water resources (FAO 2012). Freshwater is a finite resource, of which an estimated 70% is used by the livestock and agriculture industries (Doreau *et al.* 2012). Agriculture uses water directly to grow crops and indirectly to grow fodder for the production of livestock.

Land and water use

Land availability is an issue that frequently arises in the discussion of sustainable agriculture. As the demand for meat grows, there is increasing pressure on producers to farm more livestock, which requires more land. The increase in livestock requires more feed, which in turn leads to farmers increasing the amount of land being cropped, often involving deforestation or an increase in fertiliser use. Currently, the livestock sector uses about 70% of available agricultural land worldwide (Oonincx & de Boer 2012). Figure 1 shows the maximum documented levels of land, feed and water use for the three main groups of livestock and two insect species, *Locusta migratoria* and *T. molitor*. For insects, data are estimates based on available feed conversion values and calculations of land and water needed to produce the feed.

The key variable in how much water is required to produce livestock is the 'feed conversion efficiency', which measures the amount of food needed to produce a given amount of the final product (meat, eggs, etc.). Insects are significantly more efficient than other livestock in terms of feed conversion because they are cold-blooded and rely on their environment to control metabolic processes, such as body temperature (van Huis 2013). To date, one study has examined the water footprint, taking into account the entire production system, of commercially produced insects. Miglietta (2015) found that for mealworms, within a commercial system, the water footprint per ton was larger than that for production of pigs and chickens. This data must be looked at within the context of the percentage of the animal which is edible, as insects are considered to be 80-100% edible compared with other livestock at 40%–50% (Lundy & Parrella 2015). When the data are re-examined, taking into account the percentage of the animal that is edible, mealworms have a lower water footprint than the other livestock (Miglietta 2015). Only limited data are available about the feed conversion efficiency, land requirements and water use of insects, and more data are required for commonly farmed species before recommendations can be made.

Emissions

There is consensus that the biggest contributor to global climate change is greenhouse gas emissions (GHGs), predominantly CO_2, nitrous oxide and methane, from fossil fuels and agricultural and industrial processes (Sachs 2015). The agricultural sector contributes the most to GHG emissions, with livestock accounting for an overall 18% of CO_2 equivalents (van Huis 2013; Sachs 2015). Studies, considering only husbandry conditions, have found that insects perform favourably when compared to beef cattle and pigs (Figs 2 and 3).

Overall, preliminary results suggest that insects produce far fewer GHGs than standard large livestock and are approximately on par with chickens on a per kilogram (kg) basis. However, studies of larger scale production have reported less optimistic figures and shown that values are largely dependent on the type of feed. A life-cycle assessment of a commercial cricket farm in Thailand found that cricket production had a smaller environmental footprint than did broiler chicken farms and that the largest footprint hot spots were in relation to grain feed production for both systems (Halloran *et al.* 2017). No other data are currently available regarding GHGs from insect production, and concrete statements cannot be made regarding their environmental benefit over other livestock. This is in part due to industrial-scale insect production relying on the same grain feed used for livestock, and it has been suggested by Lundy and Parrella (2015) that feeding bio-waste could make insect production more environmentally viable. Lundy and Parrella (2015) used three organic waste sources as feed: a low-quality unprocessed food waste, a

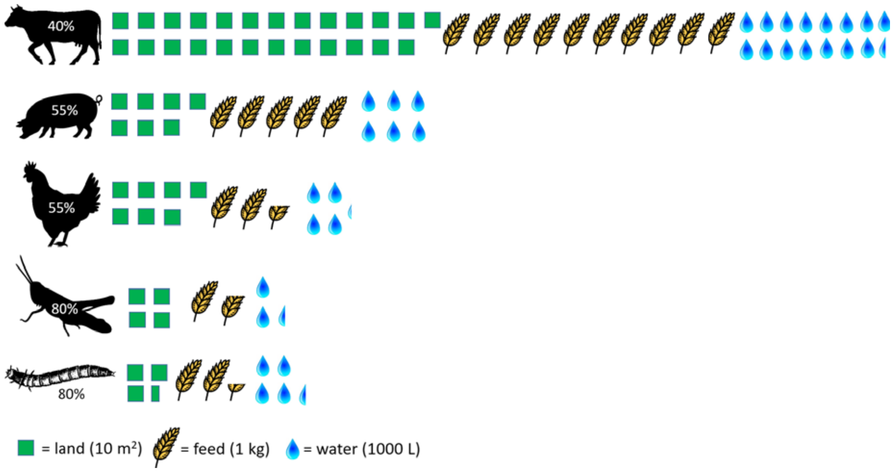

Figure 1 Amount of land, feed and water needed to produce 1 kg of live animal weight and percent of the animal which is edible. Data from Hoekstra (2012), Hoekstra and Mekonnen (2012), Mekonnen and Hoekstra (2010, 2012), Oonincx and de Boer (2012) and van Huis (2013). [Colour figure can be viewed at wileyonlinelibrary.com]

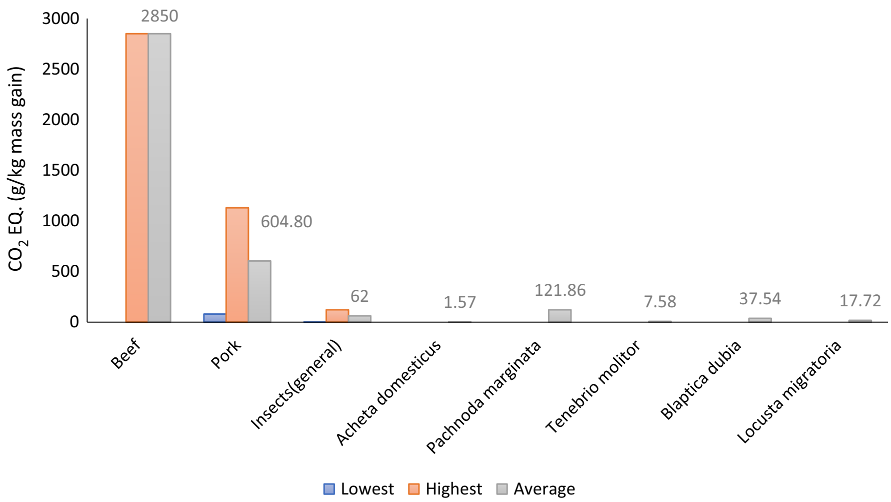

Figure 2 Production of carbon dioxide (CO_2) equivalents (EQ.) during rearing of livestock and insects. Data taken from Oonincx *et al.* (2010). [Colour figure can be viewed at wileyonlinelibrary.com]

predominantly straw-based feed and a filtrate from food waste processed via enzymatic digestion. It was found that crickets did not grow on the two unprocessed feeds, but the processed filtrate gave harvestable size insects with food efficiency equal to, or better than, chickens. Insects can be competitive as an alternative protein source only if they can outperform chickens. It has been demonstrated that black soldier flies can be reared on faecal waste, making them ideal for aiding manure disposal (van Huis 2013). Overall, organic waste is probably the best option for insect rearing, but the specific sources need to be determined for each species.

Another factor to consider in the livestock industry is the global warming potential associated with transport, slaughter and storage of meat, which contributes 17%–25% of GHGs (Oonincx & de Boer 2012). As there is currently no uniform method for processing insects, such equivalent values cannot be assessed. It is also unclear whether future regulations will restrict insect slaughter at the production facility (as they do with livestock), which would introduce transport costs.

Use in animal feed

The cost of producing meat, fish and soya bean meal as feed for animals accounts for 70% of the production costs of livestock (van Huis 2013). Insects, on the other hand, are comparably high in nutrients, have a

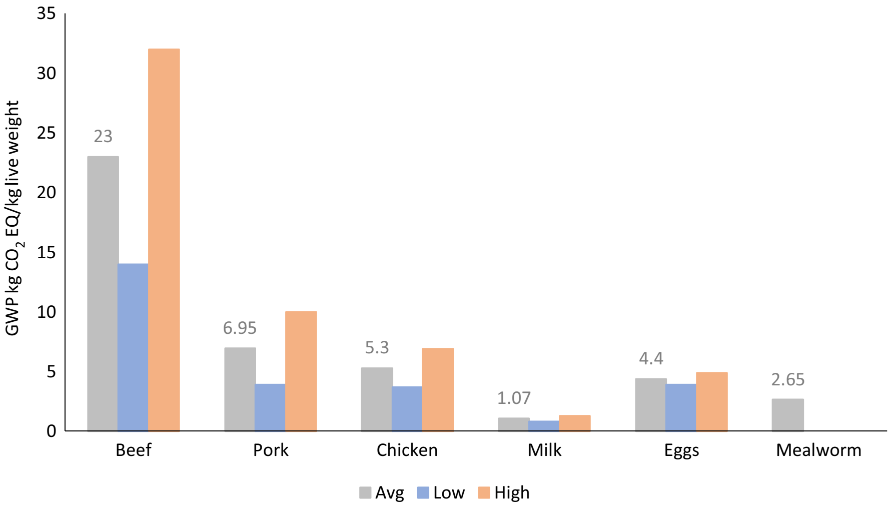

Figure 3 Global warming potential (GWP) of production of staple foods and an insect (mealworm, *T. molitor*). CO_2, carbon dioxide; EQ, equivalents. Data taken from de Vries and de Boer (2010) and Oonincx and de Boer (2012). [Colour figure can be viewed at wileyonlinelibrary.com]

low environmental impact, require less space and are already part of the natural diets of pigs, poultry and fish, making them an ideal feed alternative (Rumpold & Schlüter 2013b). Incorporating insects into broiler poultry feeds has been reported to result in no reduction in growth rates and in some cases increased chick growth rates (Rumpold & Schlüter 2013b). Replacement of soya bean oil with black soldier fly larvae has been shown to have no influence on growth or performance of broiler chickens, suggesting it is a viable alternative (Schiavone *et al*. 2017).

In laying hens, better feed conversion was seen in hens with insect meal in their diet; however, there was more variation in egg sizes (Marono 2017). Similar results of increased feed conversion and growth rates on insect meal diets compared to a standard soya bean control were seen with Barbary partridges (Loponte 2017).

Aquaculture (the farming of fish, crustaceans and other aquatic animals) is one of the fastest growing industries. However, a major hurdle to sustainable growth of the industry is the cost of feeds, particularly fishmeal and fish oil (van Huis 2013). Approximately 10% of fish production is recycled into fishmeal, and ocean fish stocks are being depleted by overfishing to provide the feed. Increasing restrictions on unregulated fishing and catch quotas have forced the aquaculture industry to search for alternative high-value protein sources for feed, which is where insects can play a valuable role. The use of insects in fish feed is not new and is widely practised by smallholder farms in Africa and Asia, who feed insects (when seasonally available) or hang lights over fish ponds to attract insects (van Huis 2013). Predominantly, black soldier flies, housefly larvae, silkworms and mealworms have been used in aquaculture feeds, but feeding trials have given mixed results in relation to both protein content and the ratio of EPA and DHA lipids to other nutrients.

Freshwater fish with omnivorous diets appear to do better on insect diets, with trials that have replaced 25% of fishmeal with black soldier flies or locusts showing no adverse growth effects for tilapia (van Huis 2013; Makkar 2014). Similarly, up to 75% of fishmeal in Nile tilapia diets has been replaced with housefly maggot meal without any adverse effects (Wang 2017). Results with mealworms fed to catfish have shown successful replacement of 40%-80% of the normal diet without adverse effects (Makkar 2014). Replacing fishmeal in carnivorous fish diets has proven more difficult. Trials with sea bass show success when up to 19.5% of the fishmeal is replaced with black soldier fly larvae (Magalhães *et al*. 2017), and for gilthead sea bream, a replacement of up to 25% or 50% of fishmeal with mealworm meal gave positive results (Iaconisi 2017; Piccolo 2017).

Economics

In addition to the environmental and nutritional benefits of feeding insects to humans or livestock, there are also economic benefits. The clearest economic picture of the edible insect trade comes from South-East Asia, where there are well-established farms and trade routes (Fig. 4) and where researchers have documented the trade most thoroughly, particularly in Thailand.

Export and import of insects for food plays a strong economic role throughout South-East Asia – the import market in Thailand alone is valued at 1.14 million USD/year (Hanboonsong *et al.* 2013). Figure 5 shows the market values for various commonly consumed insect species in Thailand compared to the market values for various other staple food sources.

Given that the market value for insects often exceeds that of other standard protein sources, insect farming can provide a stable income for established farmers. Medium-sized farms, which produce roughly 500–750 kg of crickets, four to five times a year, can get net incomes of 4270–9970 USD in a country where the average yearly gross national income per capita is approximately 5640 USD (World Bank 2016). Although data on the insect market in Africa are limited, the financial benefits of insect trading are evident in Namibia where collections and sales of mopane caterpillars (*Gonimbrasia belina*) provide valuable income (a 50 kg bag sells on average for 71.43 USD) and act as a barter item (Thomas 2013). Estimates place the value of insects as food and feed for the combined market in the US, Belgium, France, UK, The Netherlands, China, Thailand, Vietnam, Brazil and Mexico at 25.1 million GBP for 2015, with a predicted growth to 398 million GBP by 2023. This growth is predicted to be largely driven by increased consumer awareness and acceptance of insects as food,

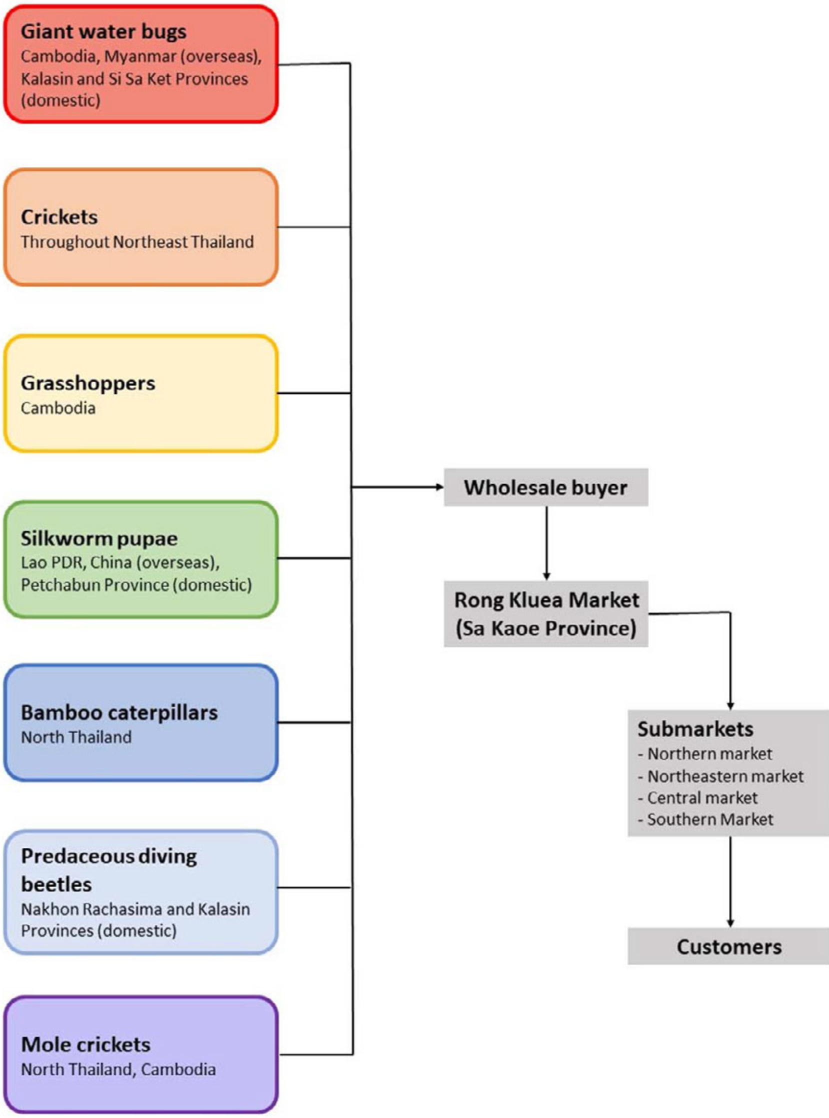

Figure 4 Collection and distribution chains of insects in Southeast Asia, reproduced with permission (Hanboonsong *et al.* 2013). [Colour figure can be viewed at wileyonlinelibrary.com]

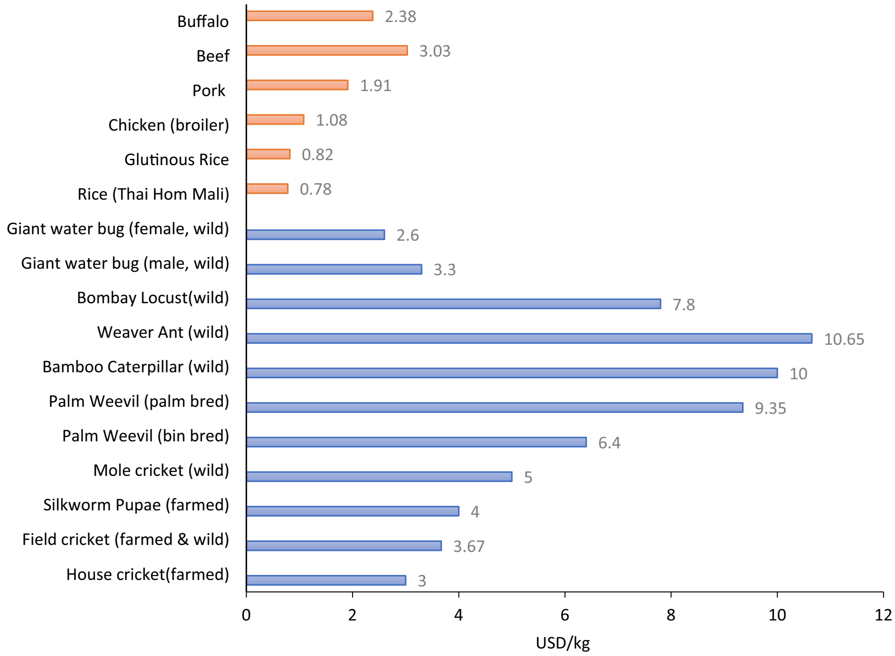

Figure 5 Market value of insects and staple foods in Thailand. Insect data from Hanboonsong *et al.* (2013), rice prices from Thai Rice Exporters Association on 2 March 2016 and meat prices from Thai Office of Agricultural Economics, values for the week of 22 February 2016. [Colour figure can be viewed at wileyonlinelibrary.com]

as well as use in animal feed (Global Market Insights Inc. 2015). In South Korea, the market, which includes insects for food, feed and medicine, is valued at 109 million GBP for 2017 with predictions that by 2020, it will have quadrupled to 348 million GBP, predicted to be driven by increased acceptance from the global community that insects play a vital role in global food security (Han 2017). These growth predictions present a great opportunity for new businesses, particularly in developing countries.

Hurdles to the use of insects as food and feed

Although a myriad of opportunities exists for entomophagy, there are significant hurdles to overcome as a result of the lack of research and the need for innovation within the sector. Major issues include the possibility that insects may contain 'anti-nutrient' properties, concerns around food safety related to storage and allergic reactions, consumer acceptability and ambiguous or non-existent regulation.

Anti-nutrient properties

Chitin is a structural nitrogen-based carbohydrate found in the exoskeleton of insects, which may have 'anti-nutrient' properties due to potential negative effects on protein digestibility (Belluco 2013). One study of seven insect species found 2.7–49.8 mg chitin per kg fresh weight and 11.6–137.2 mg/kg in dry matter (Finke 2007). A study comparing dried honey bees and honey bee protein concluded that the removal of chitin improved the quality of the insect protein as measured through protein digestibility, amino acid content, protein efficiency ratio and net protein utilisation (Ozimek *et al.* 1985). On the other hand, chitin is notably high in fibre, and chitin extracts from the exoskeletons of shellfish have been approved by relevant authorities and are readily used in Japan as a source of fibre in cereals (DeFoliart 1992). Although chitin is usually considered to be indigestible by humans (Bukkens 1997), chitinolytic enzymes, produced by bacteria from human gastrointestinal tracts, have recently been found, suggesting that chitin and chitosan can be digested (Paoletti *et al.* 2007; Dušková *et al.* 2011; Rumpold & Schlüter 2013a).

In a 2-week trial with healthy adult males, chitosan, a derivative of chitin, ingested at a dose of 3–6 g/day, resulted in a significant decrease in total serum cholesterol and an increase in serum high-density lipoprotein (HDL)-cholesterol (Koide 1998). It has also been suggested that for poultry, chitin has a positive effect on the immune system and thus may reduce the need for antibiotic use (van Huis 2013). However, the effect of long-term ingestion of chitin is unknown (Koide 1998), and more research is required in this area to understand the impact of chitin on human health and animal health.

The potential toxicity of some compounds in insects is also of concern. There are two categories of toxic insects: cryptotoxics and phanerotoxics. Cryptotoxics contain toxic substances from either direct synthesis or by accumulation from their diet. Phanerotoxics have specific organs that synthesise toxins (Belluco 2013). Commonly consumed insect species are not in either category, and studies of the levels of hydrocyanide, oxalate, phytate, phenol and tannins in edibles insect species have found that values fall well below levels of toxicity for human consumption (Ekop *et al.* 2010; Shantibala & Lokeshwari 2014). Analysis of the larvae of *Cirina forda* has confirmed that oxalate and phytic acid levels are well within safe ranges and that they contain no tannins (Omotoso 2006). A further clinical trial that fed Sprague-Dawley rats varying levels of freeze-dried mealworm powder over a 90-day period found no toxic effects (Han 2016). Overall, data on anti-nutrient properties of edible insects are limited, and more research is required.

Microbial risks

Spore-forming bacteria and enterobacteriaceae have been reported in mealworms and crickets, with higher levels found in insects that had been crushed – likely due to the release of bacteria from the gut (Klunder 2012). For the species examined (*Gryllotalpa africana, R. phoenicis, Bematistes alcinoe*), the main bacteria identified were from the genera *Bacillus* and *Staphylococcus,* and the majority of the microbes were saprophytes (Amadi & Kiin-Kabari 2016). Analysis of edible insects for the Belgian market identified that all untreated fresh insect samples had an aerobic mesophilic microorganism, yeast and mould count higher than the Good Manufacturing Practice limits for raw meat (FDA 2017); however, introducing a simple blanching step in the processing reduced levels to below accepted limits (Megido 2017). Further research indicates that treating insects the same as other foodstuffs of animal origin during processing (*i.e.* washing and thorough heating) sufficiently reduces the risk of bacteria-borne disease (Grabowski & Klein 2016).

While harmful bacteria such as *Salmonella* have been detected in insects that were in close contact with livestock (Belluco 2013), research suggests that the majority of the contamination comes from the gut microbiota of the insect (Rumpold 2014). Starving insects for 24–48 hours prior to slaughter has been suggested as a way to reduce harmful bacteria in the gut, although the one published study in this area reported that this approach had no significant impact on microbiota levels (Wynants 2017), and unpublished studies also support this finding (Larouche *et al.* 2017). Some risk of mycotoxins has been identified, but this has been studied only in the two emperor moth species (*Imbrasia belina* and *Bucnaea alcinoe*), with strains identified predominantly in the intestinal tract or from outside contamination (Simpanya & Allotey 2000; Braide & Oranusi 2011). These risks may be mitigated with evisceration and appropriate processing steps, as is done with other meat sources.

Studies on the level of organic and metal contaminants (*e.g.* polychlorinated biphenyl, DDT, dioxin compounds, heavy metals) in both whole edible insects and insect-based food items in Belgium found that all contaminant levels were generally lower than that was found in other common animal products (Poma 2017). This study indicates that consuming insects presents no more of a microbial or contaminant risk than consuming other meat sources, when the same good practice standards of preparation are applied.

Little is known about how to safely store insects to reduce microbial risk. Research has shown that freshly boiled insects spoil rapidly at room temperature (28°C) but remain stable at 3–5°C over a 2-week period; microbial levels in dried insects have also been reported to be stable at room temperature (Klunder 2012).

The European Food Safety Authority (EFSA) published a risk profile examining hazards relating to insects as food and feed, considering the entire production chain. EFSA came to the overall conclusion that if the currently permitted feed materials are used as the growth substrate for the insects, the possible occurrence of significant microbial hazards is comparable to other sources of protein of animal origin (EFSA 2015). Further systematic work is required to establish the safe shelf-life of edible insects, both for human and animal consumption.

Allergens

Many arthropods, which includes insects, arachnids, myriapods and crustaceans, are known to induce allergic reactions in susceptible individuals, caused by the presence of tropomyosin, arginine kinase, glyceraldehyde 3-phosphate dehydrogenase and haemocyanin (Belluco 2013; Srinroch 2015). Cross-reactive allergies have been identified in crustaceans, cockroaches and dust mites. One study identified a positive cross-reaction between mealworm proteins and individuals with known dust mite and crustacean allergies (Verhoeckx 2013; Van Broekhoven *et al.* 2016). A study on crickets (*G. bimaculatus*) showed a cross-reaction to crickets in individuals with known prawn allergies (Srinroch 2015). In this study, an additional novel allergen was identified in the cricket, hexamerin1B (Srinroch 2015). A recent systematic review of studies examining cross-reactivity/sensitivity with insects in individuals with known arthropod allergies has indicated that all patients demonstrated allergic reactions to insects (Ribeiro & Cunha 2017). In addition to direct consumption, there is evidence to support contact allergy sensitivity in individuals frequently exposed to insects; for example breeding farm workers (Jensen-Jarolim & Pali-Schöll 2015).

The data on allergen risk to insects are limited as the majority of trials to date have been conducted with a small number of participants ($n < 20$); however, these studies point in the direction that individuals with crustacean allergies will react negatively to insects and that there may be several additional novel insect allergens to consider.

Mass production

For insects to be considered a viable microlivestock, it must be possible to produce them on a large scale in a sustainable, safe and efficient way. It is frequently forgotten that large-scale domestic rearing of insects has been occurring for over 7000 years for sericulture (silk), apiculture (honey), biological control of pests and the production of medicinal products and shellac (Rumpold & Schlüter 2013b). Significant advances have been made with artificial rearing diets and controlled conditions for mass rearing. However, there are still several hurdles preventing the scaling up of insect farming for human and animal consumption. First and foremost, an ideal candidate insect species for mass rearing must be identified. Domestication has occurred for several thousand years with silkworms, and it has been documented that domestic silkworms can no longer effectively cling to branches and would die in the wild (Defoliart 1995). Crickets and palm weevils are mass reared in Thailand, but they are not the ideal species as they are reared on high-quality chicken feed. The ideal insect species would have high egg production, high egg hatch, a short larval stage, optimum synchronisation of pupation, high weights of larvae or pupae, a high productivity (*i.e.* high conversion rate and high potential of biomass increase per day), low feed costs, low vulnerability to diseases, ability to live in high densities and a high-quality protein content (Rumpold & Schlüter 2013b). The search for such an insect continues, although the black soldier fly (*Hermetia illucens*) does meet the above criteria, the issue of optimisation of farming techniques remains.

The majority of livestock and agricultural production systems have some level of automation, reducing the expense of manual labour. This is not the case for the majority of insect farms where manual labour is still required to complete tasks such as feeding, collection, cleaning and rehousing (Rumpold & Schlüter 2013b). This dependence on manual labour means that farm-reared insects are expensive, even when feed costs are low. There are a handful of companies that have developed automation, but these are still in trial phases. Thus, in order for insects to be an attractive alternative to protein sources such as beef and poultry, automation must be further developed to bring down the price of the end product.

In addition to the labour costs, the conditions in the rearing facility such as temperature, light, humidity, ventilation, rearing containers, population density, oviposition sites, feed and water availability, feed composition and quality and microbial contaminants must be controlled at the optimum levels for successful mass production (Rumpold & Schlüter 2013b).

Processing

As with any livestock system, farmed insects must be processed for human consumption or use in feed products. There are a myriad of standards governing the processing of conventional livestock, but there are no best practices in place for insects, largely due to the lack of data on the impact of different processing techniques on food safety and nutritional content. As discussed above, trials have examined aspects of microbial safety; however, there is still no standard processing procedure in place for insect farmers. Ultimately, an ideal insect production system would be as shown in Figure 6 (*i.e.* an efficient system with a clear set of standards and production protocols).

The only component not considered in Figure 6 is the identification of ideal feeds, and this can be a major hurdle to the sustainable mass production of insects. At present, established insect farms use predominantly poultry feed, which results in a system not significantly superior to poultry production. Utilising bio-waste sources, particularly food waste, has been lauded as the ideal for insect farming. However, aside

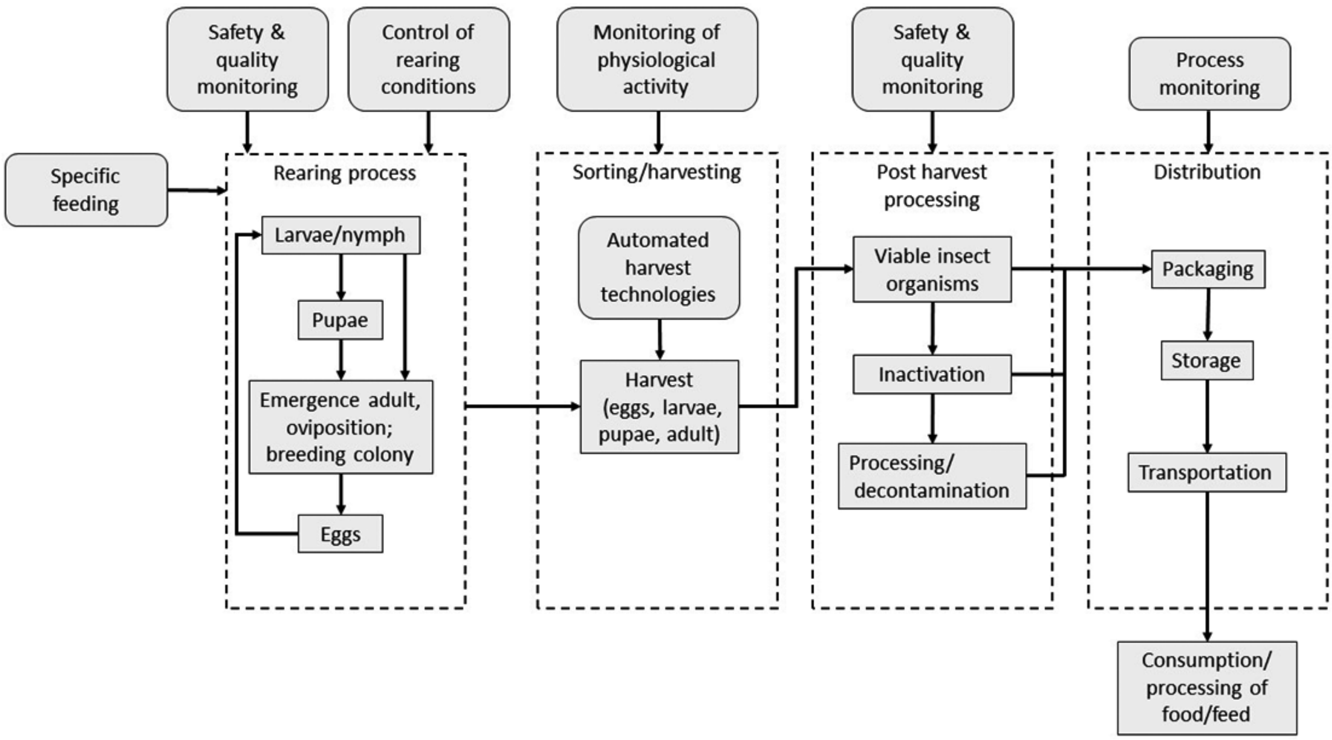

Figure 6 Model insect production system, reproduced with permission from Rumpold and Schlüter (2013b).

from one trial (Lundy & Parrella 2015), research to date on bio-waste feed sources for commonly consumed edible insects has used small colony sizes, not reflective of mass-rearing practices (*e.g.* Oonincx 2015).

Regulations

For countries where eating insects is traditional, there are no regulatory hurdles to their production, marketing and consumption. However, in Western countries, regulations present a significant barrier to the use of insects in both feed and food. EFSA has stated that all insect products for human consumption will be considered a 'Novel Food' and must be submitted for Novel Food approval by 2018, with a 2-year transition period allowing already approved products to stay on the market until 2020 (IPIFF 2017). However, some European Union (EU) Member States have their own legislation to circumvent this requirement. The Netherlands is working closely with researchers to draft legislation and, in Belgium, the Federal Agency for Safety of the Food Chain has endorsed certain insect species to be allowed as food (Belluco *et al.* 2017). With the occurrence of Brexit, it is unclear whether the UK will still follow the EFSA ruling or proceed with its own approval process under the Food Standards Agency (FSA), where decisions would presumably no longer need to be ratified by EFSA, perhaps giving more legislative freedom.

Similar rules surrounding novel food approval are in place in North America. In Canada, regulatory approval must come from the Canadian Food Inspection Agency and Health Canada, and in the US from the Food and Drug Administration, as well as the Ingredients Definition Committee of the Association of American Feed Control Officials for feed ingredients.

The use of insects in animal feed has less challenging regulations to overcome and, as of July 2017, insect proteins were approved for use in fish feed within the EU. These insects must still be raised according to the conventional livestock regulations, meaning that they cannot be fed any form of waste product, reducing the environmental benefit of rearing insects as discussed above.

The regulatory issue of insect welfare is also one of uncertainty. There is ample research and regulation regarding the necessary welfare conditions for traditional livestock, but these regulations explicitly exclude invertebrates, leading to debate about how to proceed with farming insect ethically (De Goede *et al.* 2013). A recent review by Lähteenmäki-Uutela (2017) examined the regulatory issues facing the EU, Canada, the US, Mexico, Australia and China, outlining that at this stage, rules on safety, marketing and farming are largely missing. If a clear set of rules regarding insects for food and feed can be established, it will facilitate the sustainable growth of the insect business; however, for now, with no clear rules, the insect business is left in limbo.

Consumer acceptability

There are two distinct psychological reactions to insects as a food source for humans. In countries where entomophagy is the norm, insects are seen as a valued protein source and knowledge on which species are edible is considered local wisdom passed down between generations. Conversely, in Western cultures, insects can invoke visceral negative reactions: 'deeply embedded in the Western psyche is a view of insects as dirty, disgusting and dangerous' (Looy *et al.* 2014). This view of insects as inedible is perpetuated by the Western media through TV shows such as 'Fear Factor' and 'I'm A Celebrity…Get Me Out Of Here!' where contestants are forced to eat raw insects to advance in the competition and show their daring. One study reported that in Western societies, only 12.8% of males and 6.3% of females were likely to adopt insects as a substitute for meat (Verbeke 2015) and another that 19% of individuals were prepared to eat insects as a meat substitute (Hartmann & Siegrist 2017). This presents the additional hurdle of how to increase acceptance of entomophagy in Western cultures.

To date, no socio-demographic factors have been linked to the willingness to eat insects (Hartmann & Siegrist 2017). Rather, the main influential factors seem to be neophobia, familiarity, interest in the environment, convenience and attachment to meat (Verbeke 2015; Gere 2017). The more neophobic, uninterested in the environment and attached to a diet that contains meat the person is, the less likely they are to be prepared to eat insects. However, if insects are presented in a convenient, appropriate and familiar form (*e.g.* insect flour in a cookie), the more willing an individual may be to try it (Megido 2016; Tan *et al.* 2017). Verneau (2016) demonstrated, in Denmark and Italy, that presenting information about the benefits of eating insects increases consumers' willingness to eat them, with the effect persisting for at least 2 weeks after the experiment. However, another study showed that providing false information about insect flour being an ingredient in bread led to lower scores of the bread's flavour, even though the bread did not actually contain the flour (Barsics *et al.* 2017).

Although acceptance of insects as a human food in Western cultures is low, there is significantly more support for insects as an animal feed. Two-thirds of 415 farmers surveyed in Belgium found it acceptable to use insects in animal feed (Verbeke *et al.* 2015). The *PROteINSECT* project reported that 66% of consumers consider fly larvae as suitable feedstuff, over 80% want to know more about insects as feed, and 75% were happy to eat animals fed on insects (PROte INSECT 2016). Perhaps the first step to increasing consumer acceptability of entomophagy is through increased use in animal feed.

Conclusion

Research to date indicates that insects could play an important role in addressing the impending protein supply crisis. Overall, insects contain sufficient levels of protein, fats and micronutrients to contribute to improvements in global health and food security, both via direct consumption and indirect use in feeds. In addition, research has demonstrated that insects can have a smaller environmental footprint and a higher economic value than other livestock protein sources; they are unlikely to pose significant microbial risks; they appear to cause allergic reactions in individuals with known arthropod allergies; and the majority of people from Western societies are comfortable with insects being used as animal feed but hesitant about consuming them directly.

Future research should address questions related to the scaling up of insect production to commercial levels, such as: how can insect nutritional profiles be improved in a systematic and consistent manner?; how can the environmental footprint of insects remain small when scaled up commercially?; how can insects be fed on a commercial scale in a sustainable way?; what do the regulations around insect farming, processing and storage need to cover?; are there any harmful effects to human or animal populations from the consumption of large quantities of insects?; what do insect supply and value chains look like depending on the specific end uses?; and how can the economic value of established insect supply chains be protected so as not to damage livelihoods?. Ultimately, only if insects are able to compete with traditional Western livestock, particularly chickens, or livestock feed within the supply-value chain and environmentally, will they be considered a viable alternative.

Conflict of interest

The authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or matters discussed in this manuscript.

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