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Edible insects are the future?

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The global increase in demand for meat and the limited land area available prompt the search for alternative protein sources. Also the sustainability of meat production has been questioned. Edible insects as an alternative protein source for human food and animal feed are interesting in terms of low greenhouse gas emissions, high feed conversion efficiency, low land use, and their ability to transform low value organic side streams into high value protein products. More than 2000 insect species are eaten mainly in tropical regions. The role of edible insects in the livelihoods and nutrition of people in tropical countries is discussed, but this food source is threatened. In the Western world, there is an increasing interest in edible insects, and examples are given. Insects as feed, in particular as aquafeed, have a large potential. Edible insects have about the same protein content as conventional meat and more PUFA. They may also have some beneficial health effects. Edible insects need to be processed and turned into palatable dishes. Food safety may be affected by toxicity of insects, contamination with pathogens, spoilage during conservation and allergies. Consumer attitude is a major issue in the Western world and a number of strategies are proposed to encourage insect consumption. We discuss research pathways to make insects a viable sector in food and agriculture: an appropriate disciplinary focus, quantifying its importance, comparing its nutritional value to conventional protein sources, environmental benefits, safeguarding food safety, optimising farming, consumer acceptance and gastronomy.

Insects as food and feed: Entomophagy: Consumer acceptance: Ethno-entomology: Nutrition: Food safety

The eating of insects in tropical and subtropical countries has been extensively reviewed by Bodenheimer[1] and DeFoliart[2]. Literature reviews per continent are also available: Africa[3], Asia[4,5], Latin America[6,7] and Australia[8,9]. Worldwide, over 2000 species of insects are consumed by human subjects[10]. Representatives from almost all insect groups are eaten: beetles (31 %), caterpillars (18 %), wasps, bees and ants (15 %), crickets, grasshoppers and locusts (13 %), true bugs (11 %), and termites, dragonflies, flies and others (12 %). In the Western world, until recently insects were never considered as food. However, the demand for animal protein is expected to increase globally by 76 % from 2005/2007 to 2050[11], while the land area used by livestock is already more than two-thirds of all agricultural land (68 %; FAOSTAT, consulted August 2015). The increased demand in this time period is mainly from developing countries (113 %), less from developed countries (27 %)[12]. Rising incomes and urbanisation drive a global dietary transition in which traditional diets are replaced by diets higher in, among others, meats[13]. Because of environmental[14], health[13] and animal welfare concerns, alternative protein sources other than conventional meat are being considered. Insects present such an alternative and can be considered either as human food and or as feed for livestock[15].

Abbreviations: AA, amino acid; EU, European Union.
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Why have insects as human food in the Western world been neglected for so long? There are several reasons. Harvesting from nature in temperate zones will not yield much, because: (1) insect species in temperature zones are smaller than in the tropics, probably due to their respiratory system (diffusion of oxygen in tracheas)[16]; (2) their occurrence is less clumped (examples are locust swarms and groups of caterpillars); (3) unavailability in winter time. Besides, Westerners have a negative attitude towards insects, which are often considered with disgust[17]. The latter is not justified, considering that <0·2 % of the total estimated insect species in the world (between 2·5 and 3·7 million[18]) are harmful for plants, man and animals[19]. The value of ecological services, such as dung burial, pest control, pollination and wildlife nutrition, have been quantified for the USA alone and is estimated to be at least US$ 57 billion annually[20]. The Western bias against insects as food[21,22] has determined for a long time the agenda of international agencies. It is only now that this attitude is gradually changing.

This is partly due to the emphasis on sustainable diets, defined as those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations[23]. The sustainability of meat consumption, in particular ruminant meat[13], has been questioned as the livestock sector is responsible for more than 14 % of all greenhouse gas emissions (CH_4 and NH_4)[24] and 59 % of the global agricultural ammonia emissions[25]. Implementing mitigation strategies in livestock production[24,26] will not be enough; dietary changes will still be needed in order to meet the 2°C temperature-increase target set by the United Nations Framework Convention on Climate Change[27,28]. To use other protein sources is another option and seaweed, duckweed, cultured meat and insects have been proposed[29]. Insects are an interesting alternative considering the low emission of greenhouse gases[30], the small land area needed to produce 1 kg protein[31], their efficient feed conversion efficiencies[15], and their ability to convert organic side streams in high value protein products[32].

First the eating of insects will be discussed in areas where they are traditional food and afterwards the recent developments in the Western world. The use of insects as feed in particular in aquaculture will be mentioned briefly. We will discuss how to farm insects to meet future demands, the nutritional value, marketing and processing, food safety and consumer attitudes. Finally, we indicate the way forward to make it a viable new sector in food and agriculture.

Insects as traditional food

It is difficult to estimate the percentage of people eating insects. National statistics do not take these food items into consideration. Therefore, the information has to be extracted from articles which often have an ethnobiological focus (see, for examples, chapter 2 of Van Huis, Itterbeeck[33]). The insects are mainly harvested from nature. Herbivorous insect species depend on food plants, and therefore their collection depends on the season. However, in every season there are certain edible insect species available which makes year-round harvesting possible. Also aquatic insect species can often be collected throughout the year. Edible insects often complement other protein sources which are not available during a certain period of the year. For example, people from Madagascar supplement their protein intake with a number of insect species during the lean season (period between exhaustion of rice reserves and rice harvest) when food prices are high[34]. Often insects provide nutrients which are not available in staple food. Bukkens[35] gives a few examples. In the Democratic Republic of Congo, caterpillars provide lysine, nutritionally complementing lysine-poor cereals. In Papua New Guinea, palm weevil larvae are consumed in combination with staples such as sago, sweet potato, yam and taro. The amino acid (AA) composition of the palm weevil larvae (lysine and leucine) complements that of the tubers which are limited in those AA. At the same time, the tubers provide tryptophan and aromatic AA which are limited in palm weevil larvae.

The harvesting and marketing of edible insects can improve livelihoods, in particular of women. Examples are: harvesting the Mopane caterpillar *Imbrasia belina* (Lepidoptera: Saturniidae) in Southern Africa is an 85 million US$ business, mainly carried out by women[36,37]; the marketing of the Edible stinkbug *Encosternum delegorguei* (Hemiptera: Tessaratomidae) in sub-Saharan African countries mainly benefits women in impoverished rural communities[38]; edible pupae of a saturniid wild silkworm, is commercially reared for sericulture in Madagascar, contribute to poverty alleviation[34].

The larvae of the African palm weevil *Rhynchophorus phoenicis* (Coleoptera: Curculionidae) are popular food throughout the humid tropics. In the Congo Basin and Cameroon, they are consumed by the majority of the inhabitants[39]. Their exploitation and trade by forest-dependent communities is an important source of income, often more than 20 % of all economic activities (agriculture, fishing, hunting, etc.). For professional collectors an average monthly income of 180–600 US$ is generated, representing 30–75 % of their household income.

However, future harvests may be threatened by overexploitation, unsustainable harvesting methods, increased commercialisation, land transformation and pesticide use[40,41]. Although permits are required to harvest non-timber forest products such as the Mopane caterpillar in national parks, a study in Zimbabwe showed that the rules to enforce them are either weak or non-existent[42]. Findings of this study suggest the need for adaptive local management systems that enhance sustainable use of the resource and at the same time regulate the harvesting and the market structure of non-timber forest products. Local populations can also be enhanced by semi-domestication measures, for example for caterpillars[43]: manipulating host tree distribution and abundance, shifting cultivation, fire regimes, host tree preservation and manually introducing caterpillars to a designated area. Another possibility is the rearing of edible insect species which will be discussed later.

Edible insects in the Western world

Already in 1885, a booklet appeared by an English entomologist *Why not eat insects*[44]. Bodenheimer[1] reviewed insect eating from all over the world in his book *Insects as human food; a chapter of the ecology of man*. Gene DeFoliart published *The Food Insects Newsletter* from 1988 to 2000[45]. Worldwide interest was generated with the publication of the Food and Agricultural Organization book *Edible insects: future prospects for food and feed security* which was downloaded more than seven million times and has been translated in Korean, French and Italian[33]. Another boost was the conference 'Insect to feed the world' jointly organised by the Food and Agriculture Organisation and Wageningen University in the Netherlands which attracted 450 participants from forty-five countries[46]. In January 2015, a scientific journal *Insects as Food and Feed* was started (http://www.wageningenacademic.com/loi/jiff).

In the USA, the interest of the private sector has been very much in the development of cricket-based products: protein bars, flour and cookies. In Europe, besides crickets, the Yellow mealworm *Tenebrio molitor*, the Lesser mealworm *Alphitobius diaperinus* (Coleoptera: Tenebrionidae) and the Migratory locust *Locusta migratoria* (Orthoptera: Acrididae) are marketed. In 2015, one supermarket chain with more than 500 outlets in the Netherlands sells burger, schnitzels and nuggets (produced by a Belgian company) which contain about 16 % of Lesser mealworm flour. In the Netherlands, the insects can also be bought freeze-dried, either in supermarkets or they can be web-ordered. A number of cookbooks have been produced, some with recipes from insects from all over the world[47] and some with insects that are locally available[48]. In the Netherlands, insect rearing companies, producing insects as pet or fish food, have set up special producing lines for insects for human consumption, in which they follow strict hygiene measures. They self-imposed protocols, such as track and tracing systems in order to guarantee food safety.

Several European countries have declared that certain insects are allowed to be produced and consumed, e.g. Belgium, Switzerland and The Netherlands. The Swiss federal food safety and veterinary office announced in 2015 that they back the sale of crickets, grasshoppers and mealworms as part of a planned revision of Switzerland's law governing foodstuff[49]. In September 2014 in Belgium, the Scientific Committee of the Federal Agency for the Safety of the Food Chain and validated by the Board of the Superior Health Council concluded: 'it seems highly unlikely that insects that were farmed under controlled, hygienic circumstances, would get infected with viral or parasitic pathogens from the farming environment or the nutrient medium. Since it cannot be excluded that pathogenic bacteria (and spores) from the production environment may infect the insects and its consumers, a heating step (minimally blanching, cooking, frying or stir frying) is indispensable before the products are put on to market or consumed'[50]. The initiatives by private enterprise are still small scale. However, with the increased interest the sector of insects as food is emerging. The sector of insect as feed will be shortly discussed.

Insects as feed

Insects can also be used as feedstock for pets, livestock and fish. The candidate insect species are the Black soldier fly *Hermetia illuscens* (Diptera: Stratiomyidae), the Common housefly *Musca domestica* (Diptera: Muscidae) and to a lesser extent mealworms, locusts/grasshoppers/crickets and silkworms. The advantage of the fly species and the mealworms is that they can be reared on organic side streams, interesting because one-third of the produce in the food and agriculture industry is wasted[51]. Low value organic products can in this way be transformed into high value protein products. The Black soldier fly can even be reared on manure but then food safety issues need to be considered. A number of companies in the world are geared up to produce tons of insect meal daily. The main challenge is the legislation. In October 2015, the European Food Safety Authority published a report about risks of insects as food and feed (http://tinyurl.com/p5dym9u). In the European Union (EU), insects as feedstock for pigs and poultry is not yet allowed, but they are used as aquafeed since 2013. Therefore, we will give this some more attention.

For the first time in history, more fish for human consumption have originated from farms than from wild capture, having reached almost parity in 2012 according to the latest global report from the Food and Agriculture Organization of the UN[52]. The production of fish from 2010 to 2030 is expected to grow by 24 % with 36 tonnes and this growth is entirely due to aquaculture[53]. The rapid growth of aquaculture means that the sector requires growing volumes of feed, which traditionally has been fishmeal and fish oil, by-catch from capture fisheries. However, capture fisheries are overexploited: 29 % of global fish stocks in 2011[52]. This makes world prices of fishmeal higher than ever and poses the need for other protein sources, such as vegetable-based feeds, primarily soya-based. However, these vegetable products have limitations due to unbalanced AA profiles, high-fibre content, anti-nutritional factors and competition with use for human consumption[54,55]. Tests conducted with Atlantic salmon showed that replacement of fishmeal with meal of the Black soldier fly is possible without adverse effects on the net growth of the fish, histology, odour, flavour/taste and texture[54].

Other livestock and fish species that have shown positive results by feeding them meal of different insect species such as Black soldier fly, Domesticated house fly, the Oriental latrine fly *Chrysomya megacephala* (Diptera: Calliphoridae), Yellow mealworm, the Domesticated silkworm *Bombyx mori* (Lepidoptera: Bombycidae) and the Variegated grasshopper

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Zonocerus variegatus (Orthoptera: Pyrgomorphidae) are: broiler chickens[56,57]; tilapia[55,58,59], African giant snail (*Achatina* spp.)[60], African catfish *Clarias gariepinus*[61–67]; and Rainbow trout *Oncorhynchus mykiss*[68,69].

Insect farming

Most insects in tropical countries are collected from nature, but efforts are made to farm the insects. The supply of the larvae of the African palm weevil in Cameroon from the wild is irregular and involves the destruction of raffia ecosystems[39]. Therefore, farming systems were developed involving the introduction of collected adult palm weevils in boxes containing fresh raffia tissues. The advantages of this system over wild harvesting are: higher production, less than a quarter of the raffia tissue needed, and production throughout the year. Also in Thailand[70] and the Democratic Republic of Congo[71] farming systems for this insect are being developed.

In Thailand, 20 000 domestic cricket farms produce an average of 7500 metric tonnes of insects annually for home consumption and for the market[70]. In Thailand, insect farming is expanding rapidly and offers significant income and livelihood opportunities for tens of thousands of Thai people engaged in insect farming, processing, transport and marketing[72].

To improve the health status of people in a province of Cambodia, the cricket *Teleogryllus testaceus* (Orthoptera: Gryllidae) is mass produced as a sustainable, cost-effective and high-quality alternative source of protein to traditional livestock[73]. For that reason, the diet of the crickets should be based on unused wild resources. Young cassava leaves and brown rice (with or without bananas) are used to produce crickets with a high total biomass, while diets made of taro aerial parts or only young cassava leaves could be used to produce crickets with high protein level.

The Yellow mealworms in Mexico were produced on wastes of vegetables and fruits[74]. Van Broekhoven, Oonincx[75] studied the effect of diets composed of organic by-products originating from beer brewing, bread/cookie baking, potato processing and bioethanol production on three edible mealworm species: the Yellow mealworm, the Giant mealworm *Zophobas atratus* (Coleoptera: Tenebrionidae) and the Lesser mealworm. Larval protein content was stable on diets that differed 2–3-fold in protein content, whereas dietary fat did have an effect on larval fat content and fatty acid profile.

When House crickets *Acheta domesticus* (Orthoptera: Gryllidae) and broiler chickens were fed grain-based diets at a scale of economic relevance, protein conversion efficiencies were similar[76]. Whether rearing crickets for human consumption will result in a more sustainable supply of protein depends, in large part, on what the crickets are fed. Very low-quality organic side-streams may not support adequate growth and survival of cricket populations. Species should be identified and processes designed that capture protein from scaleable, low value organic side-streams, which are not presently consumed by conventional livestock.

Nutrition

It is difficult to generalise the nutritional value of insects, because it varies with species, gender, developmental stage, diet and the environment (temperature, humidity and photoperiod) and even with the analytical methods used[77]. Many species are rich in protein and fat, essential AA and fatty acids as well as vitamins and minerals[35,78]. They will be reviewed briefly.

Protein content

The protein content on a dry-matter basis of insects range between 7 and 91 %; and many species contain approximately 60 % protein[77]. The digestibility of protein from insects is highly variable, partly because a part of the AA in cuticular protein is bound to chitin, a polysaccharide and component of the exoskeleton of insects. According to Rumpold and Schlüter[78], who compiled 236 nutrient compositions, edible insects in general meet the requirements of the WHO for AA with high values for phenylalanine + tyrosine and sometimes being rich in tryptophane, lysine and threonine. In particular, the species from the order Orthoptera (grasshoppers, crickets and locusts) are rich in proteins and represent a valuable alternative protein source. Most edible insects provide satisfactorily the required essential AA. Yi *et al.*[79] extracted and characterised protein fractions from three mealworm species and one cricket species. They concluded that protein content of the insect species was comparable with conventional meat products. Promising in terms of future food applications is that insect proteins can form gels using the soluble fractions obtained by a simple aqueous extraction procedure.

Fat content

After protein, fat represents the second largest portion of the nutrient composition of edible insects, ranging from 13 % for Orthoptera (grasshoppers, crickets, locusts) to 33 % for Coleoptera (beetles, grubs)[78]. The larvae of the African palm weevil are considered a delicacy in Nigeria. The lipid content (on a dry weight basis) of this larva (67 %) is higher than the amount found in most conventional protein foods such as beef, chicken, egg and milk[80]. In developing countries, this can be an advantage as malnutrition there is often more a problem of energy deficiency than protein deficiency[81]. The fatty acids of insects are generally comparable with those of poultry and fish in their degree of unsaturation, but contain more PUFA[77,78].

Micronutrients

Most species of insects contain little calcium because insects as invertebrates do not have a mineralised skeleton[77]. Several insect species, such as crickets, palm

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weevils, termites and caterpillars were shown to be rich in content of zinc and iron. This is interesting as the proportion of the world population at risk for zinc deficiency is more than 17 % for zinc[82] and 25 % for iron deficiency[83]. In a study in Kenya, crickets and termites proved to have a high iron and zinc content. Assuming a bio-availability of 10 %, 10 g crickets would cover 114 % of the recommended nutrient intake for iron for adult males and 53 % for adult females; these figures for zinc are 36 and 51 %[84]. In the Democratic Republic of Congo, the benefits were investigated of a cereal made with caterpillars and used as a micronutrient-rich supplement to complementary feedings in infants aged between 6 and 18 months[85]. Infants aged 6–12 months were provided with 30 g caterpillar cereal daily and infants aged 12–18 months with 45 g (100 g containing 1840·96 kJ (440 kcal), 23 g protein, 21 g fat, 40 g carbohydrate, and 12·7 mg Fe and 12·7 mg Zn). Infants in the cereal group had higher Hb concentration and fewer were anaemic, compared with the usual diet. However, it did not reduce the prevalence of stunting. Results of the mineral composition of African palm weevil shows that a 100 g sample of the insect will meet the recommended daily intake for iron, zinc, copper, manganese and magnesium[80]. In Cambodia, micronutrient fortification in rice-based complementary food products was studied using animal sourced food such as the local fish and tarantula spider *Haplopelma* sp. (Araneae: Theraphosidae)[86]. The latter is eaten in Cambodia and traded in local food markets. The spider was used because of its high content of zinc (16 mg zinc/100 g raw weight). However, more studies are needed on the bioavailability of minerals in human subjects from edible insects. Concerning vitamins, insects are generally low in retinol but rich in riboflavin, pantothenic acid, biotin and in some cases folic acid[77,78].

The estimated number of newborns with sickle cell anaemia globally will increase by one-third from about 305 800 in 2010 to about 404 200 in 2015, of which 79 and 88 %, respectively, are in sub-Saharan Africa, particularly in Nigeria and the Democratic Republic of Congo[87]. In the Katanga Province of the Democratic Republic of Congo, methanol extracts from nine insect species, among which two are edible, were tested for antisickling activity[88]. The non-edible caterpillar *Chrysiridia madagascariensis* (Lepidoptera: Uraniidae) showed 60 % inhibition, while the edible caterpillar *Elaphrodes lactea* (Lepidoptera: Notodontidae) had an inhibition effect of 11 %. A few examples will be given of the potential use of insects in medication.

Yoon *et al.*[89] administered ground Japanese rhinoceros beetle *Allomyrina dichotoma* (Coleoptera: Scarabaeidae) larvae on high-fat-induced-obese mice. Visceral fat was reduced, suggesting potential for developing it as a nutritional supplement or pharmaceutical intervention against obesity. Also the development of parkinsonism in mice could be blocked by a homogenate of adults of the Lesser mealworm[90]. This is an unexplored area of research in which edible insects may have a beneficial health effect.

Processing and marketing

Processing methods can have an effect on the nutritional value of edible insects. For example, in Kenya, toasting and solar drying reduced protein digestibility and niacin content of the grasshopper *Ruspolia differens* (Orthoptera: Tettigoniidae) and the riboflavin and retinol content of winged termites of the species *Macrotermes subhylanus*[91].

In Mexico, tortillas supplemented with Yellow mealworm powder had excellent consumer acceptance[92]. The powder contained 58 % protein (rich in essential AA such as phenylalanine, tyrosine and tryptophan) and had a fatty acid composition of 20 % oleic acid and nine linoleic acids (determined by GC–MS).

In Korea, muffins prepared with different concentrations (up to 8 %) of Yellow mealworm powder in basic flour had acceptable sensory properties, such as flavour and taste, while total polyphenol content and antioxidative activity increased with the concentration of the powder[93].

Food safety and legislation

Food safety is of special importance when dealing with new food sources. In the context of edible insects, there are four ways through which food safety risks can arise, i.e. (1) the insect itself could be toxic; (2) the insect could have acquired toxic substances or human pathogens from its environment during its life cycle; (3) the insect could become spoiled after harvest; (4) consumers could experience an allergic reaction to the insect.

Some toxic insect species are eaten. In Southern Africa, the edible stinkbug is consumed[94]. The insect has a defence chemical that stains the skin and affects vision. Yet, protective gear is not worn. This necessitates nocturnal harvesting when the insect is immobilised by cold. The local population uses preparation methods to remove the defence chemical, making the insect palatable. Another toxic species is the Variegated grasshopper, called in French 'criquet puant' (stinking locust), which is eaten in West Africa[95]. When molested, they secrete a liquid of which the odour is repulsive to man[96]. The Mofu in Northern Cameroon call the insect in their local language the 'poison locust'[97].

Acquisition by edible insects of toxic substances or human pathogens is very well possible and that is the reason that insects should be produced hygienically. For example, spore-forming bacteria can be introduced through soil contact and the Mopane caterpillar is often sun-dried on the soil. Therefore for this caterpillar, Mujuru *et al.*[98] stressed good harvesting and manufacturing practices to prevent contamination. To prevent physical, chemical and biological contamination during the food production process, the Hazard Analysis and Critical Control Points system is a widely used approach[99], and should be adopted by commercial edible insect producers and companies developing insect-based food products.

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Klunder *et al.*[100] evaluated the microbiological content of fresh, processed and stored Yellow mealworm larvae and House crickets[100]. A short heating step eliminated Enterobacteriaceae. Preservation techniques other than the use of a refrigerator are drying or acidifying. Lactic fermentation of composite flour/water mixtures containing 10 or 20 % powdered roasted mealworm larvae resulted in successful acidification and was demonstrated effective in safeguarding shelf-life.

Some people have an allergy towards either house dust mites and/or crustaceans, and the question is whether they would have the same allergic reactions towards insects, another order of the arthropod phylum. Crustaceans, long considered to be taxonomically widely separated from insects, are actually closer[101]. Cross-reactivity does seem to occur. The allergen arginine kinase was found to be responsible for cross-reactivity between the prawn *Macrobrachium* spp. and the field cricket, *Gryllus bimaculatus* (Orthoptera: Gryllidae)[102]. Verhoeckx *et al.*[103] concluded that there is a realistic possibility that patients allergic to house dust mites will react to food containing Yellow mealworm protein. The effect of thermal processing (frying) can alter the allergenicity of edible insects. This was investigated with sera allergic to shrimp using the Bombay locust *Patanga succincta* (Orthoptera: Acrididae), a major agricultural pest in Thailand, but also popular food[104]. Proteins identified as locust allergens in raw and fried locusts differed except for hexamerin being present in both: enolase and arginine kinase in raw locusts and pyruvate kinase, enolase and glyceraldehyde-3-phosphate dehydrogenase in fried locusts. Food allergic reaction to other insect species, such as grasshoppers and locusts, have been reported[105].

The legislation concerning edible insects has been reviewed in the EU[29]. Insects are already sold as food in several EU countries although when not consumed 'in a significant degree' before 15 May 1997, they may be considered novel food. The Novel Food Regulation does not seem to apply to whole insects as the definition states 'food ingredients isolated from animals'[106]. The existing legislation was not conducive; private enterprises had little incentive to invest in development and production[107]. However, since 25 November 2015, insects have been declared novel food and are subject to a simpler, clearer and more efficient authorisation procedure centralised at EU level (EU Regulation 2015/2283).

In the USA, edible insects fall under the Food, Drug and Cosmetic Act[108]. Insects are considered food if that is the intended use (Sec. 201f). Food insects must be clean and wholesome (i.e. free from filth, pathogens, toxins), must have been produced, packaged, stored and transported under sanitary conditions, and must be properly labelled (Sec. 403). The label should include the scientific name of the insect. Insects must be raised specifically for human food following current Good Manufacturing Practices.

Issues that need to be taken into account are: clean rearing substrate (free of mycotoxins, pesticides or heavy metals); thermal or another treatment before consumption; mention on label expiry date and a warning that people allergic to crustaceans could react similarly to consuming insects; remove wings and legs (e.g. locusts); buy only insects from insect rearing companies that have set up special production lines for human consumption.

Consumer attitudes

In the Western world, insects have never been on the menu, and there is a strong rejection of insects as human food. Even in the tropics where insects are traditionally eaten, this is not a general practice and in urban areas the same aversion may exist. With increasing affluence, Western lifestyles and eating patterns are often copied and insects as food are not part of it. Also the biased notion that the eating of insects is a 'peculiar habit of primitive man[1], or starvation food[22], will not help in its popularisation. The practice may diminish in less developed countries with increasing urbanisation, which went from 18 % in 1950 to about 50 % now and 64 % in 2050[109]. The continuation of the practice means that a marketing strategy should be in place to bring it to city markets.

The disgusting reaction in the Western world appears to be entirely acquired, arising in the period between the age of about 2 and 5 years. It is not primarily based on the sensory properties of potential foods, but rather on knowledge of the nature or history of a potential food. Interestingly, disgust has been identified as the main reason for persons totally rejecting insects as food[110]. It has been proposed to harness disgust as a positive feature of insects, what Rozin *et al.*[111] called benign masochism.

Are people willing to consider eating some form of insect food? The majority of two non-consuming groups from a completely different cultural background, USA (72 %) and India (74 %), were willing to do so[110]. Gender seems to have an effect; men, both in Belgium[112] and the USA[110] are more likely to adopt insects as a substitute for meat. Familiarity and experience with the food is also important for its acceptance. In Thailand, people are culturally exposed to edible insects which are considered in terms of taste and familiarity[113]. However, Thai participants were strongly repulsed by mealworms, due to the association with larvae that they often see in decaying matter. This association was absent amongst the Dutch participants who were more familiar with mealworms as food.

A number of strategies are proposed to facilitate insect consumption:

1. *Giving people a taste experience, the so-called 'bug banquets'*[17]. Consumers in Australia and The Netherlands, who had eaten insects before, had a more positive attitude towards entomophagy than the people who had not[114].
2. *Providing information about the benefits of edible insects*. In India and the USA, the most common perceived benefits of edible insects were related to nutrition and environmental sustainability[110]. Benefit perception is derived from heuristic information processing and personal experience[115].

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3. *Processing insects into familiar products*. In Kenya, termites and lake flies were baked, boiled and steam cooked under pressure and processed into crackers, muffins, sausages and meat loaf[116]. Consumers, familiar with edible insects accepted these processed insects readily and it facilitated commercialisation. It has also been suggested that gradually increasing concentrations of insects in flour might be effective[110]. This has been called the bottom-up approach, contrary to the top-down approach in which expensive restaurants have insects on the menu (see next point).
4. *Use role models*. For example in The Insect Cookbook, interviews were conducted with the former secretary general of the United Nations Kofi Annan as well as with the chef cook of one of the best restaurants (Noma, Kopenhagen, Denmark) in the world[48]. This restaurant and the D.O.M. restaurant in Saõ Paulo, Brazil, where insects are served, have both been declared in 2015 among the ten best in the world (http://www.eater.com/2015/6/1/8699487/the-worlds-50-best-new-restaurants-2015).
5. *Indicating the systematic proximity in animal classification between insects and crustaceans*. This could facilitate the integration of entomophagy in our feeding habits and behaviours[117]. Insects and crustaceans are more closely related than was generally thought[101].
6. *Providing information about food safety*. In the USA, half of the respondents perceived microbes and disease as a risk of eating insects[110]. Conversely, the majority of the respondents in Australia and the Netherlands indicated that there were no risks associated with eating insects. Information was seen as trustworthy when provided by scientific researchers, persons familiar with using the product, the government and well-known relatives, but not when promoted by food producers or famous persons[114]. Risk perception is likely to be derived from deliberative information processing[115].
7. *Gastronomy*. Deroy *et al.*[118] argued that rational arguments using environmental and nutritional benefits will not be enough to change insect-related food behaviours. Acceptability should be based on food perception: making it delicious.
8. *Availability*. Edible insects, of which the quality and food safety is guaranteed, should be available. Besides the price should be affordable.

Way forward

Disciplinary focus

In a number of countries but also at the Food and Agricultural Organization of the UN, edible insects are hosted by the Forestry Department as edible insects are classified as non-wood forest products. However, edible insects do not only come from forests, and certainly they become part of agriculture when farmed as mini-livestock. Disciplines involved are: food and nutrition, agriculture (food production), animal husbandry (as they can be reared as feed for livestock), fisheries (as feed in aquaculture) and biodiversity (resources being threatened).

Ethno-entomology

The number of edible insect species per country is strongly influenced by the amount of research effort of some researchers who were interested in the topic, e.g. Ramos Elorduy in Mexico[6] and Malaisse in the Democratic Republic of Congo[119]. Therefore, it is likely that there are still many species not yet identified as being edible. A systematic effort in insect-eating countries to identify the number of insect species used for human consumption is necessary. At the same time, information needs to be gathered on when and how the insects are collected, prepared, consumed, conserved and marketed. At the same time the consumption of insects may also have medicinal uses.

Statistics on edible insects

More information is needed about the extent of insect consumption and trade. Insects' contribution to the nutrient intake is also poorly known since data are absent in food composition tables and databases. Recently FAO/INFOODS collected and published analytical data from primary sources with sufficient quality in the Food Composition Database for Biodiversity (BioFood Comp)[120].

Nutrition

Although quite some studies have been conducted on the nutritional values (summarised by Bukkens[35], Finke and Oonincx[77] and Rumpold and Schlüter[78]) more data on the quality of insect proteins compared with plant proteins and other animal proteins are required as well as on fatty acid composition, mineral and vitamin content. The methods to determine nutritional quality should be standardised. How we can regulate, enrich and add certain food ingredients such as the *n*-3 fatty acids, EPA and DHA via feed is an interesting question.

Environment

Except for one life cycle analysis study conducted on one farm for the Yellow mealworm[31], there are no other studies concerning energy, greenhouse gas production and land area. This is urgently needed in order to establish its environmental impact *v.* other protein sources. Little is known about the water footprint; only one study indicates that it is more efficient to obtain protein from mealworms rather than from traditional farmed animals[121]. One of the major advantages is that a number of insect species can be reared on organic side streams. The question which side streams can be used in order to achieve high feed conversion efficiency and high-quality insects is a major area of research.

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Food safety

This is an area which still requires extensive research. In particular when organic side streams are used, the question is which kind of side streams are suitable and how is the insect dealing with possible chemical contaminants, such as dioxins, polychlorinated biphenyls, heavy metals, pesticides, fungicides, and antibiotics. Processing of insects can have an effect on the formation of toxic substances or process contaminants, such as heterocyclic aromatic amines, polyaromatic hydrocarbons, acrylamide, chloropropanols and furans. The way to conserve the insects and its effect on shelf life needs to be studied. Cross-reactivity of insect consumption by people having an allergy to house dust mites or crustaceans need to be established.

Insect farming

Questions that need to be researched are: What is the appropriate harvest time of the farmed insects in relation to nutritional content? What are the possibilities of de-gutting (fasting) or gut-loading? How to scale-up the production process, and making it less labour intensive by automating and mechanising it? One of the advantages of insects *v.* conventional livestock is that we have many different species that can be used. Which species can fit which purpose? An unexplored area is the use of different strains of insect species. Can we genetically improve certain characteristics of insects by breeding them (e.g. breeding for resistance to diseases)? The short life cycle of insects offers certainly possibilities. It is expected that insects adapt quickly to the imposed rearing conditions, which companies optimise to have the highest output. In crop protection, we have acquired quite some knowledge about entomopathogens and how to use them to control insects. However, we know very little about insect diseases that emerge when rearing them in large production units: biological and genetic characterisation, phylogeny, host range, transmission, persistence, epidemic potential and safety for man. And how do we prevent diseases, and if they occur how do we control them? Several publications have looked at the possibility of using edible insects as food on a spaceship. Species need to be chosen that can function in a bioregenerative small-scale life support system in which insects function at the same time as recyclers and decomposers. Species that have been proposed are in particular the Domesticated silkworm *B. mori* (Lepidoptera: Bombycidae)[122–124] and the Yellow mealworm[125].

Gastronomy and consumer attitudes

Earlier in this paper, a number of strategies which may influence consumer acceptance of edible insects have been mentioned. Emotional and psychological factors have to be addressed. The basis of rejection of edible insects should be investigated and ways developed how to overcome this. Consumer groups should be identified and targeted that are most likely early adopters; and as stated by Deroy *et al.*[118] acceptability of insects as a sustainable food source should be based on food perception, requiring a close collaboration between cognitive neuroscience, human sciences and gastronomic science.

Insects have a lot of potential in food and feed production. This may well become a new agricultural and food sector. Despite the recent interest in this topic worldwide, we are still at a preliminary stage and a lot of effort is needed by private and public partner to realise its potential.

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A. van Huis reviewed the literature and wrote the manuscript.

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