Potential of Insects as Food and Feed in Assuring Food Security

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Abstract

With a growing world population and increasingly demanding consumers, the production of sufficient protein from livestock, poultry, and fish represents a serious challenge for the future. Approximately 1,900 insect species are eaten worldwide, mainly in developing countries. They constitute quality food and feed, have high feed conversion ratios, and emit low levels of greenhouse gases. Some insect species can be grown on organic side streams, reducing environmental contamination and transforming waste into high-protein feed that can replace increasingly more expensive compound feed ingredients, such as fish meal. This requires the development of cost-effective, automated mass-rearing facilities that provide a reliable, stable, and safe product. In the tropics, sustainable harvesting needs to be assured and rearing practices promoted, and in general, the food resource needs to be revalorized. In the Western world, consumer acceptability will relate to pricing, perceived environmental benefits, and the development of tasty insect-derived protein products.

INTRODUCTION

Entomophagy: human consumption of insects

Sustainability: ability to maintain productivity without compromising the needs of future generations

Food security: "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (1996 World Food Summit Plan of Action, nr. 1)

Insects form part of the human diet in many tropical countries (16, 36). Yet, entomophagy is often not promoted by national governments, and the focus is on Westernized dietary patterns as the standard to be emulated (40, 152). In Western countries, human consumption of insects is infrequent or even culturally inappropriate, resulting in its rarely being discussed as part of the sustainability and food security agendas of international organizations and donor agencies (**http://www.fao.org/forestry/edibleinsects/65424/en/**). Entomophagy is often considered as a peculiar habit practiced by "primitive man" (16) in tropical countries. Bodenheimer (16), in his 1951 book *Insects as Human Food: A Chapter of the Ecology of Man*, showed that it is more than a mere curiosity, and he lists an impressive number of examples of entomophagy being practiced all over the world. Even earlier, in 1921, Bequaert (15) presented an overview of entomophagy but clearly indicated that it was not his intention to furnish arguments to include insects in the Western diet. However, the rapidly growing world population and depletion of our resources require rethinking of our food patterns and habits, particularly those relating to meat consumption. This review explores whether it is timely and appropriate to start considering insects as sustainable and viable food and feed resources that can contribute to assuring global food security.

Detailed ethnoentomological research has been conducted on entomophagy practiced by specific tribes on certain insect orders, e.g., the studies by Silow in Zambia (131, 132). Thanks to G.R. DeFoliart, who was the editor of the *Food Insects Newsletter* in the 1990s (37) and who wrote an online bibliography (36), awareness in the Western world was created as he outlined the benefits of insects as human food (40) and animal feed (38). A number of review articles on entomophagy have subsequently appeared, either focusing on a particular part of the world, such as Africa (144), Australia (29), Latin America (123), and Southeast Asia (154), or discussing a certain topic, such as biodiversity (41) or nutrition (23). Efforts are being made to list all species of arthropods eaten worldwide, and the number now stands at approximately 1,900 (**http://www.ent.wur.nl/UK/Edible+insects/Worldwide+species+list/**). Since 2010, the Food and Agricultural Organization of the United Nations has been assessing the potential of insects as food and feed for assuring food security (**http://www.fao.org/forestry/edibleinsects/74848/en/**). What are the forces driving us to consider insects as food and feed globally?

NEED FOR ALTERNATIVE PROTEIN SOURCES

Rising incomes and rapid urbanization in developing countries, particularly in Asia, are creating shifts in the composition of global food demand (97). Wealth is a major determinant in the increase in global meat consumption (141). Per capita meat consumption in high-income countries is expected to increase by 9% in 2030 (from 86 kg capita^{-1} year^{-1} in 2000), whereas for China an increase of almost 50% is expected (from 49 kg capita^{-1} year^{-1} in 2000); this will also increase the demand for coarse grain as feed for livestock, namely 48% and 158%, respectively (97). Demands for grain and protein-rich feeds are closely related to meat consumption (143): For every kilogram of high-quality animal protein produced, livestock are fed approximately 6 kg of plant protein (118). The increase in world prices for the most important agricultural crops will lead to an increase in prices for beef, pork, and poultry of more than 30% by 2050 compared with 2000 (102). The same study indicates that the situation may be aggravated by climate change, causing prices to increase by an additional 18–21%. Food scarcity may become even more serious when taking into account rising demand for biofuels and decreased agricultural productivity: Productivity of land and labor grew at a substantially slower rate from 1990 to 2005 than from 1961 to 1990 (9). The increase in food and feed prices in the future will prompt the search for alternative protein sources, e.g., cultured meat (53), seaweed (59), vegetables and fungi (12), and mini-livestock (115).

Mini-livestock: domesticated, small animals, including arthropods, reared as food and feed

Greenhouse gas (GHG): gas that absorbs and emits radiation within the thermal infrared range

Life cycle assessment: assessment of environmental impacts associated with all stages of a product's life

Feed conversion ratio (FCR): measure of an animal's efficiency to convert feed mass into increased body mass (kilogram feed:kilogram weight gain)

BENEFITS OF MINI-LIVESTOCK COMPARED TO LIVESTOCK

Greenhouse Gas and Ammonia Emissions

Greenhouse gas (GHG) emissions from livestock production (including transport of livestock and feed) account for approximately 18% of global human-induced emissions (137). Methane (CH_4) is produced by enteric fermentation (31% of global emissions) and released from manure (6%); N_2O is released mainly from feed crop fertilizer and manure (65%). A review of the literature indicates that 1 kg of beef has the highest environmental impact when measured in CO_2 equivalents (14.8 kg), followed by pork (3.8 kg), and chicken (1.1 kg) (54). Concerning the global anthropogenic atmospheric ammonia emissions, responsible for eutrophication of surface waters and acidification of soils, almost all is emitted by the agricultural sector, of which almost two-thirds is by livestock (137). Insects can also produce GHG and ammonia. Methanogenic bacteria occur in the hindguts of tropical species of cockroaches (Blaberidae and Blattinae), termites (Isoptera), and scarab beetles (Scarabidae) (62). However, most commercially reared edible insect species such as the yellow mealworm (*Tenebrio molitor*), the house cricket (*Acheta domesticus*), and the migratory locust (*Locusta migratoria*) compare more favorably than conventional livestock, not only in terms of direct emissions of GHG but also in terms of ammonia production (113). However, a life cycle assessment of an edible insect species product should still be conducted and compared with that of conventional meat.

Feed Conversion Ratio

Feed conversion ratios (FCRs) are particularly important, as an increased demand for meat will cause a more than proportional demand for grain and high-protein feeds. FCRs vary widely depending on the class of animal and the production practices used to produce the meat. However, a very rough calculation from average figures can be made. From long-term statistics for the United States, the following FCRs were given: 2.5 for chicken, 5 for pork, and 10 for beef (134). There are few studies on FCRs for edible insects. Different FCR values are given for *Acheta domesticus*: 0.9–1.1 depending on the diet composition (101) and 1.7 for fresh weight (31). The difference is probably due to longer feeding and later harvesting in the second study (21 days versus 45 days). The proportion of edible weight differs considerably between conventional livestock and insects. The percentage of edible weight for chicken (58) and pork (both 55% of liveweight) is higher than that for beef (40%) (135). Crickets in the last nymphal stage can be eaten whole, but when eaten as a snack, some prefer that legs (17% of total weight) be removed, and because the chitinous exoskeleton (3%) is indigestible, the percentage edible weight amounts to 80% (101). Using the aforementioned figures, the FCR of edible weight can be calculated, showing crickets to be twice as efficient as chickens, 4 times more efficient than pigs and 12 times more than cattle (**Table 1**). These calculations can also be made for protein efficiency. That would be helpful if the protein content was very different for livestock and crickets, but it is not: Poultry, pork, and beef show values of 200, 150, and 190 g protein per kilogram edible weight, respectively (58), whereas for cricket nymphs and adults, these figures are 154 and 205 g, respectively (55). It is most likely that crickets convert feed more efficiently to body mass than do conventional livestock because insects are poikilothermic and their growth stages do not invest metabolic energy in

Table 1 Efficiencies of production of conventional meat and crickets

	Cricket	Poultry (135)	Pork (135)	Beef (135)
Feed conversion ratio (kilogram feed:kilogram liveweight)	1.7 (**31**)	2.5	5	10
Edible portion (%)	80 (**101**)	55	55	40
Feed (kilogram:kilogram edible weight)	2.1	4.5	9.1	25

maintaining a constant body temperature above ambient values. Other insect species are therefore likely to show similar efficiencies.

Zoonoses

High-density animal production operations can also increase the incidence of livestock disease, and the emergence of new, often antibiotic-resistant pathogens. Infectious diseases of livestock cost the global community billions of euros every year, e.g., avian influenza (H5N1), foot-and-mouth disease, bovine spongiform encephalopathy (BSE), and classical swine fever (74). Meat consumption in high-income countries has also been associated with human health problems such as BSE (74) and cardiovascular disease and cancer (114). Zoonotic infections are increasing and pose significant threats to human health, such as the new influenza A (H1N1), which is closely related to the swine influenza A (142). Because insects are taxonomically much more distant from humans than are conventional livestock, such risks are expected to be very low.

Water Use

The international virtual water flows related to trade in livestock and livestock products are quite significant (nearly half of the volume of virtual water flows relates to feed crops) (28). This is because the virtual water content of livestock products is very high compared with that of cereal crops, in particular, that of beef at 22,000 liters kg^{-1} produced (28); other publications even mention 43,000 liters, mainly because of indirect water inputs such as forage and grain feed crops (117). In China the larger amount of meat in diets has already caused water scarcity in the period 1961 to 2003 (84). The figures for some reared edible insect species are expected to be much lower, considering that, for example, the yellow mealworm and the lesser mealworm (*Alphitobius diaperinus*) are drought resistant, can be reared on organic side streams (122), and have efficient FCRs. However, studies confirming this still need to be performed.

Virtual water: water used to produce a commodity

Organic side stream: all flows of organic waste from households, agriculture, and the food manufacturing industry to final disposal

BIOCONVERTING ORGANIC SIDE STREAMS INTO ANIMAL AND FISH FEED

Can organic side streams be used as feed for insects to contribute to the sustainable management of biowaste while at the same time creating a high-protein product? Globally, one-third of all food produced is wasted, amounting to 1.3 billion tons per year (61) and, in particular, to methane as a contributor to anthropogenic GHG emissions (17). In developing countries waste collection and inadequate treatment of waste is an increasing problem, and often one- to two-thirds of waste is not collected (44). One policy is to reduce organic waste disposal, but another possibility is its valorization. Conversion of organic refuse into compost by saprophages such as earthworms and microorganisms is a well-known procedure (128). However, a number of insects, e.g., larvae of the black soldier fly (BSF) (*Hermetia illucens*), the common house fly (*Musca domestica*) (47, 109), and certain mealworm species (42), can also be used for this purpose.

BSF is an especially interesting candidate for converting organic refuse (44). It can convert dairy, poultry, and swine manure to body mass, reducing dry matter mass by up to 58% (130) and associated nutrients such as P and N by 61–70% and 30–50%, respectively (100). The larvae also reduce *Escherichia coli* counts (86) in dairy manure and *Salmonella enterica* serovar *enteritidis* in chicken manure (49). Problematic house fly populations are also decreased in chicken manure (20, 129). BSF larvae can also reduce and recycle fish offal from processing plants (136). BSF larvae grown on 1 kg of cattle, swine, and poultry manure have a high fat content that allows the production of 36, 58, and 91 g of biodiesel, respectively (83). House fly larvae have been grown on municipal organic waste (109) and the yellow mealworm on dried and cooked waste materials from fruits, vegetables, and cereals in various combinations (122). Wastewater sludges have also been used to mass-rear the codling moth, *Cydia pomonella*, for the production of granulovirus for biocontrol (21).

Compound feed: feedstuffs blended from various raw materials and additives and formulated according to the specific requirements of an animal species

Most of the experiments have been done on a laboratory scale. Developing and standardizing mass-rearing techniques on an industrial scale could become a new economic sector. However, there are still a number of challenges, both biotic and abiotic, that need to be addressed, e.g., rearing, automation, and safety issues related to pathogens, heavy metals, and organic pollutants.

INSECTS AS FEED INGREDIENTS

Insects can be used as a replacement for fish meal and fish oil in animal diets. Global industrial feed production in 2011 was estimated at 870 million tons, worth approximately US$350 billion (**http://www.ifif.org**). Meal and oil from both fish and soybean are used for compound aquafeed and animal feed. Fish meal and fish oil were derived from 20.8 million tons (19%) of the global fish production of 145 million tons in 2008 (50). This concerned mainly small, pelagic forage fish (139). The worldwide production of fish meal and fish oil in 2006 was 5.46 and 0.95 million tons, respectively [processing yields of 22.5% and 5%, of which 68% and 89% were used in aquaculture, respectively (139)]. Aquaculture has grown from providing 4% of global fish supplies by weight in 1970 to 38% in 2008 (50), and production is estimated to grow at more than 8% a year. Not only this growth but also marine overexploitation, from 10% of stocks in 1974 to 32% in 2008 (50), increases the costs of producing fish oil and fish meal (43, 139). Prices of soybean and soy oil have also increased due to a rapid expansion in demand (particularly in China) caused by a growing world population, whereas growth in production has slowed (143). With world prices of feed ingredients increasing, the industry is looking for alternative protein sources. There is much interest in possible replacements for these expensive ingredients (51). The most promising insect species for industrial production are BSF, the common house fly, the yellow mealworm, the lesser mealworm, silkworm (*Bombyx mori*), and several grasshopper species (see 10).

BSF larvae convert manure to body mass containing 42% protein and 35% fat (130), which makes them a suitable source of feed for both livestock (103) and fish (19). When fish offal was included in their diet, their lipid content increased, including omega-3 fatty acids, making BSF larvae a suitable replacement for fish meal/oil in fish and livestock diets (136). Substituting 50% of the fish meal by fish offal–enriched BSF allowed growth of rainbow trout similar to that of a fish meal–based control diet (127).

House fly maggots have also been proposed as poultry feed in both Western (155) and tropical countries (13, 66, 140). They can convert poultry manure and at the same time produce pupae as a high-protein (61%) feed with a well-balanced composition of the amino acids arginine, lysine, and methionine (47). Diets containing 10–15% maggots (which appear during biodegradation of chicken droppings using house flies) improved carcass quality and growth performance of broiler chickens (66). Furthermore, dehydrated fly larvae compared favorably to soybean meal as a protein supplement for turkey poults (155). The rearing technology for fly larvae needs to be further developed, as large volumes are required for supplementing commercial poultry diets. An automated process for growing and harvesting the larvae will be required for this technology to become commercially feasible.

Acridids are an attractive and important natural source of food for many kinds of vertebrate animals, including birds, lizards, snakes, amphibians, and fish (10). The Chinese grasshopper (*Acrida cinerea*) could replace 15% of chicken diets containing soybean meal and fish meal from 8 to 20 days posthatching without any adverse effects on broiler weight gain, feed intake, or FCR (149). The grasshopper *Zonocerus variegatus* can replace fish meal for rabbits (107).

The yellow mealworm has been shown to be an acceptable protein source for African catfish (*Clarias gariepinus*) (104) and for broiler chickens (122). Silkworm (*B. mori*) pupae mash was successfully used as a replacement for fish meal in poultry diets, supporting both growth and egg production (150). Similar results were obtained with silkworm (*Anaphe infracta*) caterpillar meal (67). In Italy, preimaginal stages of *Spodoptera littoralis* have been evaluated to replace fish meal as possible feed for rainbow trout (33).

FARMING INSECTS

Most edible insects are harvested in the wild. However, insects such as silkworms and honey bees have been domesticated for a very long time because of their by-products, although in both cases the insects themselves are also eaten (16). Another insect that is domesticated is cochineal (*Dactylopius coccus*), which yields the carminic acid used as red dye in human food as well as in the pharmaceutical and cosmetic industries. In Peru they are either harvested from prickly pear plants growing in the wild or planted as live fences around houses. In Mexico cochineal are grown in environment-controlled microtunnels made of transparent plastic, on *Opuntia ficus-indica* var. *atlixco* (7). Environmental manipulations to procure edible insects could be considered as semicultivation. The most prominent examples of this are (*a*) harvesting edible eggs of aquatic hemipterans from artificial oviposition sites in lakes in Mexico; (*b*) deliberately cutting palm trees in the tropics to trigger egg laying by palm weevils (*Rhynchophorus* spp.) and the subsequent harvesting of larvae; and (*c*) manipulating host tree distribution and abundance, shifting cultivation, implementing fire regimes, managing host tree preservation, and manually introducing caterpillars to a designated area to promote the abundance of arboreal, foliage-consuming caterpillars in sub-Saharan Africa (145).

Recent examples of edible insects being commercially farmed for human consumption include the house cricket, the palm weevil (*Rhynchophorus ferrugineus*), the giant water bug (*Lethocerus indicus*) in Thailand (Y. Hanboonsong, personal communication), and water beetles in China (69). However, when promoting insects as food and feed, procedures for large-scale rearing need to be developed. This is a challenge for industries specialized in the mass rearing of insects for biocontrol, sterile insect technique, and pet feed (18). The major issues in mass rearing are quality, reliability, and cost-effectiveness. In addition, pathogens such as the *A. domesticus* densovirus can constitute a serious problem in commercial rearings in the United States and Europe (138). This pathogen does not seem to affect the cottage industry rearing of this cricket species in Southeast Asia.

When produced as animal feed or human food, insects should compare favorably to conventional protein products. It is technically feasible to mass-produce insects for human consumption using industrial methods (78). Whether automation is economically interesting depends largely on labor costs. Furthermore, automation has the advantages of increased product performance and consistency, reduction in microbial contamination by personnel, and increased space utilization (116). Insects such as the silkworm (*B. mori*), the termite *Macrotermes subhyalinus*, and the drugstore beetle (*Stegobium paniceum*) have been considered for space-based agricultural systems because they can recycle waste material (72). A drugstore beetle growth reactor large enough to provide 100 people with animal protein occupies only 40 m^3 (77).

CONSERVATION

Insects are generally considered a nondomesticated resource, as few species are reared. Caterpillars gathered in the wild have a comparative advantage over those edible species gathered from crops as they are free from pesticides. However, overexploitation has led to the disappearance of mopane caterpillars (*Imbrasia belina*) from parts of Botswana (87) and South Africa (68). To address this problem some community leaders have placed embargos on harvesting during certain periods (90), but modeling has shown that this may not lead to sustainable harvesting of the larvae (6). The logging of commercial sapelli trees (*Entandrophragma cylindricum*) in the Central African Republic threatens the survival of the important caterpillar *Imbrasia oyemensis* (147). To allow regeneration of the tree species, the present forest concession rules require loggers to leave at least one seed tree of sapelli for every 10 ha of logged forests. This may result in a significant reduction in the caterpillar supply as well as in the regeneration of young sapelli trees, as harvesting caterpillars is more easily done by cutting down the trees. In Benue State, Nigeria, 10 most preferred and consumed insect species have been identified, but deforestation, water pollution, and bush burning reduce their availability (3). In Mexico, 14 edible insect species were documented as threatened due to overexploitation or ecosystem degradation (121). Overexploitation may occur because of the higher demand resulting from an increase in human population or when harvesting is carried out by nonnative and nonqualified independent harvesters. For example, when collectors did not respect harvesting rotations of the weaver ant *Oecophylla smaragdina*, they depleted this resource in Indonesia (26). Ecosystem degradation may occur due to pollution (aquatic Hemiptera) or pesticide use (*Aegiale hesperiaris* in agave) (121). In France, until the mid-1980s, mayflies (*Ephoron virgo*), also called manna, were collected in large quantities by local fishermen along the Saône River and sold to middlemen and traders to be mixed into animal feed (mainly for farm birds) (27). However, development of the river banks very likely degraded mayfly habitat. Possible measures to conserve insect populations include documenting their significance to people's livelihoods, assessing the links between insect collection and the ecosystem, and enforcing legislation.

However, methods conducive to insect survival and reproduction should also be developed, e.g., providing food resources, creating suitable habitats, harvesting sustainably (e.g., allowing repair of ant and wasp nests), and employing (semi)rearing like that being done for wild silkworms. In the last case, the African wild silkmoth *Gonometa postica* was reared in semicaptivity by using net sleeves on the branches of host plants to protect the larvae against predators and parasitoids (105). Other practices include the transfer of edible caterpillars to trees near the homestead (80) or to other tree species to improve their flavor (131).

CONTROLLING INSECTS BY USING THEM AS FEED AND FOOD

In the tropics there are numerous examples of pests that are also used as food and feed (24, 35, 80). Governments may even encourage people to consume insects in order to control plagues, as was the case during a locust plague in Thailand (153). However, control is often not intended; e.g., in Niger women can earn more money by marketing edible grasshoppers caught in their millet fields and harmful to the crops than by trading the crop itself (144). However, there are very few examples in which harvesting insects is considered a control method. For example, in Vientiane Province, Laos, electric-light water traps were placed facing rice fields, but their primary aim was to capture edible insects and not to control pests (A. van Huis, personal observation). Grasshoppers such as *Oxya chinensis*, also edible but harmful to crops, were collected in rice fields in Indochina by drawing nets or baskets over the young rice plants (16). In Mexico chemical control and manual harvesting of an edible insect pest species were compared. The grasshopper *Sphenarium purpurascens*, a pest of corn, bean, alfalfa, squash, and broad bean in Mexico, Guatemala, and some Caribbean islands, is often controlled using organophosphorus pesticides. However, it is also a key species in the Mesoamerican diet, and for that reason the insect is manually harvested very early in the morning, after which it is sold on the market. Manual harvesting in alfalfa reduced egg densities significantly but proved less effective than insecticide spraying (25). However, besides the other negative side effects inherent in the latter method, a potential food is contaminated. Also, in the Philippines harvesting of several edible insect species, e.g., a migratory locust (*Locusta migratoria manilensis*), a mole beetle (*Gryllotalpa* sp.), a June beetle (*Leucopholis irrorata*), and the Korean bug (*Palembus dermestoides*), is reported to serve as a control strategy (1).

Conflicts may arise in national chemical control campaigns against pest insect species that are used as feed or food (35). During the winter of 1988/1989, locusts invading Kuwait were sprayed with insecticides, even though the local population consumed them. Chemical analysis showed high amounts of phosphorus- and chlorine-containing pesticide residues in the samples (126). In other cases, introducing pesticides reduces biodiversity in field ecosystems, endangering natural food resources. For example, in aquatic rice fields in Laos, 200 species of fish, amphibians, crustaceans, mollusks, and insects supply a range of nutrients to villagers (108). Of the nine insect species investigated, only the cricket *Gryllus testaceus* had the highest protein content and contained high-quality fatty acids (148). This indicates the importance of refraining from pesticide use under such circumstances.

One example in which biological control can be combined with the practice of entomophagy is provided by weaver ants of the genus *Oecophylla*, which are effective predators of many pest species in orchards (146). As it happens, queen brood is a popular food item in Thailand and Laos and large amounts are marketed. In mango plantations in Thailand, feeding the ants with cat food and sucrose produced at least twice as much brood per tree as with unfed ants, and the harvest was sustainable and compatible with biological control (110).

NUTRITION

At least 50 publications focus on the nutritional value of insects as feed and food, some concentrating on specific regions in the world and others concentrating on protein or fatty acid content of specific species. Because the nutritional composition of the 1,900 edible insects so far recorded is highly variable, it is difficult to generalize as to their food value (23, 34). Not only species but also development stage and diet are likely to be important determinants of nutritional composition (112).

Protein quality in relation to human requirements is measured by amino acid profiles and digestibility. In Nigeria four popular edible insect species (*Imbrasia belina*, *Rhynchophorus phoenicis*, *Oryctes rhinoceros*, *Macrotermes bellicosus*) have been shown to contain all essential amino acids, with relatively high amounts of lysine, threonine, and methionine, which are the major limiting amino acids in cereal- and legume-based diets (46). However, amino acid profiles differ so much among edible insect species that it is recommended that the protein quality be analyzed in relation to that of the dietary staple (23). For example, lysine is commonly the first limiting amino acid in cereals, but the termite *M. bellicosus* in Nigeria complements this deficiency (23). Similarly, in Papua New Guinea the protein of the staple food tubers such as yam, taro, and sweet potato are limited in lysine and leucine, but the larvae of *Rhynchophorus bilineatus* are a good source of these amino acids

(23, 93). In Botswana the use of *I. belina* as a high-protein food component for children has been explored (111), and in Kenya its addition to weaning food was most promising (8).

The fat content of food insects is variable among species, but the highest values are found in termites and palm weevil larvae (23). The saturated/unsaturated fatty acid ratio of most edible insects is less than 40%, comparing favorably with poultry and fish, although the content of polyunsaturates, linoleic and linolenic acids, is higher in insects (39).

When evaluating the importance of entomophagy, the focus has often been on protein content. However, the very high amounts of important micronutrients in insects, in particular, iron and zinc, may be of considerably greater importance (95). Iron and zinc deficiencies are widespread in developing countries, especially in children and women of reproductive age: Approximately 2 billion people are deficient in zinc and 1 billion have iron-deficiency anemia (98). Termites and crickets, commonly eaten among the Luo in Kenya, have high iron and zinc contents (30). However, additional studies are required to determine the bioavailability of iron and zinc from insects.

In some traditional methods of processing edible larvae, the gut content is removed by applying pressure on the caterpillar from the head downwards between the collector's fingers (90). The opposite of degutting, gut loading, can be practiced for commercially raised insect species (56). Gut loading has been studied for house crickets, yellow mealworm larvae, and silkworm (*B. mori*) larvae and has proved effective in increasing the calcium/protein ratio (64) and vitamin A content (56).

Gut loading: providing animals with a high-quality diet prior to being consumed

Hazard Analysis and Critical Control Point system: a systematic preventive approach for quality assurance that identifies, evaluates, and controls physical, chemical, and biological hazards throughout the food/feed production process

Chitin (the main component of the arthropod exoskeleton), chitosan (produced by deacetylation of chitin), and chitooligosaccharides (degraded products of chitosan or chitin) have attracted considerable interest because of their biological activity, which includes immunity-enhancing effects (82, 99, 124, 151) and both promoting the growth of beneficial bacteria and inhibiting the growth and activity of pathogenic microorganisms (73, 85, 99). For example, 15% shrimp meal (2.8% chitin) in broiler chicken diets resulted in increased populations of intestinal *Lactobacillus* and decreased intestinal *E. coli* and cecal *Salmonella* (73). For that reason, insect products may prove interesting for replacing the use of antibiotics to treat and prevent infectious bacterial diseases in poultry and livestock feed, because the emergence and spread of antibiotic-resistant bacterial strains of *Campylobacter* sp., *E. coli*, and *Enterococcus* sp. from poultry products to consumers pose human health risks (11, 74).

Allergies are an increasing problem in Western populations living in hygienic environments, whereas the prevalence of allergies remains much lower in developing countries burdened with poverty and poor hygiene (22). The hygiene hypothesis suggests that the exposure to chitin-containing intestinal parasites during childhood explains the aforementioned asymmetric prevalence of allergy in populations (22). Would an increase in consumption of chitin through promotion of insects as food in early childhood protect against allergy later?

FOOD SAFETY

When developing food/feed from edible insects and insect-based ingredients, potential safety issues regarding consumers and animal health should be identified and mitigated (e.g., microbial, chemical, toxicological, and allergenic risks). The Hazard Analysis and Critical Control Point system is a preventive system adopted by the Codex Alimentarius Commission (52). There have been incidences of problems with food safety throughout the world. For example, the ataxic syndrome that occurs after the consumption of the African silkworm *Anaphe venata* is particularly common in southwest Nigeria in the rainy season (2). The period of wide availability of larvae coincides with the occurrence of the seasonal ataxia, a neurological disorder. It has been suggested that this may occur in poorly nourished persons who are marginally thiamine-deficient because of a monotonous diet of carbohydrates containing thiamine-binding cyanogenic glycosides. A seasonal exacerbation of their thiamine deficiency from thiaminases in seasonal foods such as this silkworm could cause ataxia. A thorough heat treatment is necessary to detoxify the enzyme in the caterpillar to make it acceptable as a safe source of high-quality protein (106).

Because of the wide acceptability and consumption of the larvae of *Cirina forda* (Westwood) (Lepidoptera: Saturniidae) in Nigeria, a toxicological study on them was conducted (5). Although oral administration of the raw extract of the larvae was toxic to mice, the commonly used local procedure of boiling and sun-drying the larvae eliminated possible neurotoxins.

After being degutted, boiled, and dried, stored mopane caterpillars may be prone to fungal infection, reducing their nutritional value (96). To maintain quality, the caterpillars should be dried quickly and evenly after harvesting and processing and subsequently stored under cool, dry conditions (133).

A heating step is sufficient for inactivation of Enterobacteriaceae; however, spore-forming bacteria, most probably introduced through soil, survive this treatment. Alternative preservation techniques without the use of a refrigerator, such as drying and acidifying, seem practical and promising (76).

PRESERVATION AND PROCESSING

Because most edible insect species are collected in the wild, they are only seasonally available, unless preservation methods allow storage for longer periods. Some insect species in Asian countries are preserved by canning, including wasp larvae, weaver ant brood, silkworm pupae, giant water bugs, crickets, and grasshoppers. However, most species offered on the market are sold live. Therefore, many are only available early in the morning. But this depends on the time of day they are caught; grasshoppers are often sold throughout the day. Shelf life can be extended by keeping them refrigerated, or they can be sold fried as ready-to-eat food. Weaver ant larvae and pupae and stink bugs being sold in markets in Thailand are placed on ice. Caterpillar species in tropical countries often undergo some processing before they are sold on the market. For example, in northern Zambia, caterpillar processing for long-term storage in the household or for sale involves the following steps: (*a*) eviscerating (degutting) live caterpillars soon after they are collected from the foliage of host plants; (*b*) roasting the eviscerated caterpillars over hot coals, from bonfires set up in the woodlands, until the setae and spine body adornments are burned off and the caterpillars become hardened; (*c*) sun-drying the roasted caterpillars until they are crispy; and (*d*) packaging the sun-dried caterpillars in sacks or other material (90).

Processing edible insects into conventional consumer products seems to encourage entomophagy, as was shown in Kenya, where termites and lake flies (Chaoboridae and Chironomidae) were baked, boiled, steamed, and processed into crackers, muffins, sausages, and meat loaf (14). Sorghum and Bambara nuts mixed with caterpillars was considered to be a protein-enriched food suitable for children 10 years of age and older (8).

Processing influences the nutritional content of the insects. Degutting the mopane caterpillar increased crude protein content and digestibility, whereas cooking lowered them, and hot coal–roasting elevated mineral content, probably due to contamination (88). Toasting and solar drying can decrease the in vitro protein digestibility and vitamin content of edible winged termites (*Macrotermes subhylanus*) and the edible grasshopper *Ruspolia differens* (75). In smoke-dried samples of *Rh. phoenicis* and *Oryctes monoceros* larvae, cholesterol concentrations were approximately 60% and 20% of those of the raw and fried samples, respectively (45).

Therefore, optimal processing methods need to be investigated to promote commercialization of insect products. In the Western world, consumer acceptance is likely to be associated with the development and implementation of an appropriate processing strategy (e.g., extracting, purifying, and using insect protein as a food additive) (32). Then characteristics of the protein need to be determined, e.g., solubility, thermal stability, and capacity to gel, form fiber, emulsify, and foam, and the sensory properties need to be established as well. For insects used as feed, the process of extracting proteins would be too expensive, but insects still need to be grown, harvested, dried, ground, and packaged. The optimal level of inclusion of these insect products in feed should be determined.

COMMERCIALIZATION

Although in tropical countries the retail price of edible insects is often higher than that of conventional meat, insects are regularly preferred, indicating how much they are appreciated as a delicacy. For example, the availability of the mopane caterpillar on the market affected the sale of beef, which was cheaper, among the Pedi in South Africa (119). In Uganda the retail price of *R. differens* is US$2.80 per kilogram, whereas beef retails at approximately US$2 per kilogram in Kampala (4). In this case the grasshopper trade is dominated by men and characterized by wholesalers who buy grasshoppers from collectors and in turn sell to retailers, who subsequently sell to consumers. The business is concentrated around urban areas, along the roadside or highway vehicle-stopping points where there are networks of distributors, sellers, and buyers. Several key barriers, however, hamper the practical trade of *R. differens*, e.g., high market dues levied to traders, among others.

As the larvae and pupae of the weaver ant *Oecophylla smaragdina*, a popular food item in Southeast Asia, can only be kept fresh for two days, profits depend on the time between harvesting and selling (26). They can also be sold after boiling and drying, however, which makes them a 20% lighter product that can still be sold for half of the original price for up to six months.

Collection of edible caterpillars in the Central African Republic is done mainly by men (85%), of which 88% are students. The selling is entirely done by women, of which 75% are students and the rest professional fruit and vegetable saleswomen; however, selling insects can become their main activity during the caterpillar season (91).

Some edible insect species are collected early in the morning or evening, making the activity compatible with other activities, and hence increasing the efficiency of income generation. In Laos earnings from collecting crickets can be greater than those from raising cattle or growing rice (94).

CONSUMER ACCEPTANCE

Knowledge about consumer preferences and barriers for using insects as human food and animal feed is scanty but necessary in order to set up commercialization trajectories. In aquaculture and aviculture, the inclusion of insects in feed will probably not be considered a problem by consumers, as insects are already natural feed for fish and birds.

Concerning insects for human consumption, (whole) insects are an accepted food item in most culinary cultures of the world, although there are taboos (81). Food acceptance is controlled by affective, personal, cultural, and situational factors, but motives are based mostly on sensory/pleasure considerations and health. Humans are inclined to avoid unfamiliar foods (neophobia), particularly when they are of animal origin (89). With these novel foods, humans exhibit both an interest in (obtaining a wide variety of nutrients) and a reluctance to (the possibility that these foods may be harmful or toxic) eating them (the omnivore's dilemma). Neophobic reactions toward novel foods of animal origin may be decreased by lowering individuals' perceptions of their disgusting properties (89). Initial disgust with respect to a certain food can be turned into a preference, e.g., sushi in the Western world. Such an example shows that food preferences are not stable and can change over time. Considering that consumer acceptance of insect food and food ingredients is a significant

Nociception: neural processes of encoding and processing noxious stimuli

barrier, broad public debate can explain the sustainability of food production systems and the need to find alternative protein sources that are acceptable. Appropriate processing strategies could be developed and implemented by transforming insects into more conventional forms (analogous to hot dogs or fish sticks) or by adding extracted and purified insect proteins to food items. Perceived risk, benefit, and control (regulation and effective labeling) are powerful determinants of consumer acceptance of novel and traditional foods (57), as are perceptions of potential environmental impact, at least for some consumers (60). Proper food risk management should include a preventive strategy, identifiable control systems that respond quickly to contain a risk, and enough information for consumers to exercise informed choice (63). Due account should be taken of the role of risk assessment and associated legislation (e.g., in relation to potential allergic reactions or other safety issues) when developing novel foods from edible insects and insect-based ingredients. These issues need to be translated into how end products should be designed, labeled, and marketed.

Animal welfare is another consideration that may be involved in consumer acceptance when insects are reared. With conventional livestock farming, most concerns relate to density of animals per surface area; this does not apply to insects, as many species usually live naturally in crowded conditions, e.g., locusts that are in the gregarious phase when reared. Another point of debate would be whether insects can perceive pain. Electrophiles, a class of noxious compounds that humans find pungent and irritating, can be detected by *Drosophila* flies (71). *Drosophila* larvae also show nociceptive behavior (rolling) when attacked by a parasitoid, but it was not clear whether the insect brain was involved or lower-level neural systems (65). Therefore, pain perception goes beyond nociception, and some data suggest that there is cognition in some invertebrates (48). This may be a reason to suggest taking good care of insects when rearing them.

Finally, consumers need to know where they can obtain the insects and how they should be prepared. This then involves marketing, advertising, and the preparation of recipe books.

CONCLUSIONS

Although insects form part of the human diet in many countries and regions of the world, their consumption is often not promoted and Western dietary patterns seem to be dominant. Western societies have never seriously considered entomophagy as an option. However, in future, meat-centric diets will become increasingly expensive and grain–livestock systems environmentally unsustainable (70). Mitigation strategies have been proposed for the meat crisis that better utilize available technologies, which could reduce non–carbon dioxide emissions from livestock production by approximately 20% if applied universally (92). These measures include reformulation of ruminant diets to reduce enteric fermentation and methane emission, capturing methane from manure to use as a source of energy, burning animal waste for fuel, and raising cattle for beef organically on grass (79). To stabilize GHG emission from livestock production, global average meat consumption should stabilize at 33 kg year^{-1} (from 17 and 82 kg year^{-1} in developing and developed countries, respectively) (92), although this would not improve nutrition of the poor in developing countries (125). Changing land use and agriculture and practicing modest meat consumption can contribute to a sustainable model of food production (135).

Insects for human consumption and as feedstock for livestock and fish could contribute to food security and be part of the solution to the meat crisis considering the low emissions of GHG, the high FCR, and the option of using organic side streams to feed the insects. At the same time, the production of insect biomass as feedstock for animals and fish can be combined with biodegradation of manure and the composting and sanitizing of waste. Grains targeted as livestock feed, which often comprise half of the meat production costs, could then be used for human consumption.

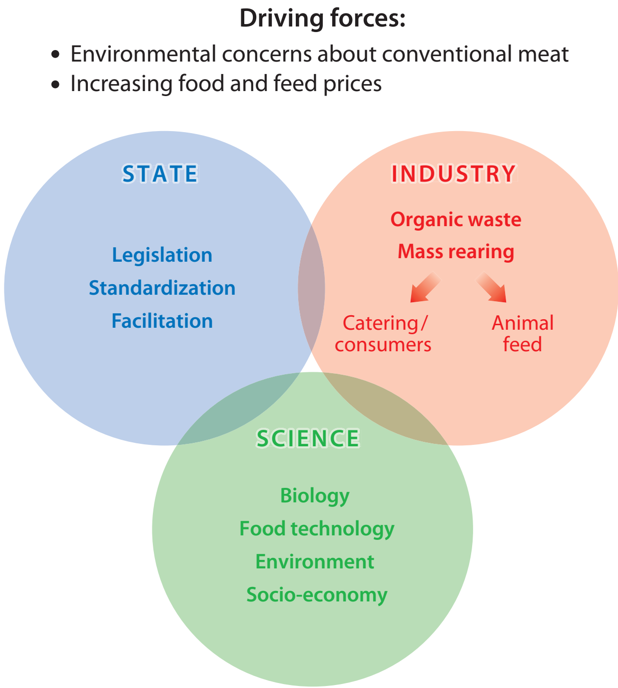

Figure 1

The interface between state, industry, and science necessary to promote insects as food and feed.

Therefore, edible insects are a serious alternative to the conventional production of meat, either for direct human consumption or for indirect use as feedstock.

A new industrial sector for insects as food and feed is ripe for development. In developing countries, the sustainable harvesting of edible insects from the wild requires a nature conservation strategy such as that proposed for honey bees and silk moths (120). Habitat manipulation measures should enhance abundance and accessibility of insect populations. The possibility of simultaneously controlling pest insects by harvesting them as food/feed could be further exploited. However, collection from the wild will not suffice to promote entomophagy, and rearing procedures for some targeted species need to be developed. A cosmopolitan species such as the house cricket is a likely candidate, considering its nutritional value, taste, and ease of rearing. Preservation and processing techniques should increase shelf life, conserve quality, and increase acceptability of insect products. Micronutrient bioavailability (particularly of iron and zinc) in edible insects needs further investigation, considering the massive occurrence of these deficiencies in the tropics.

The feedstock industry would require immense quantities of insect biomass in order to replace present protein-rich ingredients such as meal and oil from fish and soybeans. Considerations for such large-scale insect production are the intrinsic rate of increase, weight gain per day, FCR, invulnerability to diseases, the potential to rear insects on organic side streams, suitability for automation, and selection of high-quality strains. As such, BSF and yellow mealworm are good candidates. The challenge for this new industry will be to assure cost-effective, reliable production of an insect biomass of high and consistent quality. Other challenges to address are food safety issues (pesticides, contaminants, heavy metals, pathogens, allergenicity) and processing procedures for transforming insects into protein meal for animal/fish feedstock or for the extraction of insect proteins to be used as ingredients for the food industry. Regulatory frameworks are presently missing, as the industry tries to be proactive in being self-regulatory. The collaboration of government, industry, and academia is often conditional to success (**Figure 1**). It is an innovative challenge demanding a multidisciplinary approach, whereas marketing and public acceptance require interdisciplinary and transdisciplinary approaches.

SUMMARY POINTS

1. The consumption of approximately 1,900 insect species harvested from nature for human consumption, mostly in developing countries, will decline if this food source is not revalued.
2. The world prices for grain, and consequently meat, will increase during the next 30 years, and this will prompt the search for alternative protein sources, among which insects are considered to be very promising.
3. The most frequently reared edible insect species (crickets, locusts, and mealworms) emit lower levels of GHG than do conventional livestock.
4. Some insect species can biodegrade organic waste and transform it into high-quality insect biomass.
5. Insects can partly replace increasingly expensive protein ingredients of compound feeds in the livestock, poultry, and aquaculture industries.
6. A challenge to insects becoming an important protein source for humans and animals is the development of cost-effective, automated mass-rearing facilities that produce stable, reliable, and safe products.
7. When entomophagy is promoted in developing countries, major challenges are to develop sustainable harvesting practices, to enhance natural populations by semicultivation, and to set up cottage industry–like rearing facilities.
8. To develop a new economic sector of insects as food and feed, a multi-, inter-, and transdisciplinary approach is required, in which government authorities, industry, and scientists need to collaborate.

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