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Potential and challenges of insects as an innovative source for food and feed production

Birgit A. Rumpold, Oliver K. Schlüter *

Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Max-Eyth-Allee 100, 14469 Potsdam, Germany

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ABSTRACT

Edible insects, a traditional food all over the world, are highly nutritious with high fat, protein and mineral contents depending on the species and thus represent a noteworthy alternative food and feed source and a potential substitute e. g. for fishmeal in feed formulae. Research is required to develop and automatize cost-effective, energy-efficient and microbially safe rearing, harvest and post harvest processing technologies as well as sanitation procedures to ensure food and feed safety and produce safe insect products at a reasonable price on an industrial scale especially in comparison to meat products. In addition, consumer acceptance needs to be established. Potential and challenges along the production chain of insects for food and feed are discussed based on published data and future research needs are derived from recent literature.

Industrial relevance text: With the increasing demand in alternative protein sources world-wide, insects represent an innovative food and feed source rich in high quality protein as well as other beneficial nutritional ingredients such as fat, minerals and vitamins. Despite traditional knowledge about insects and their harvest in the wild, for the industrial mass production of safe insects and insect products for consumption and for processing into food and feed, the development of rearing, harvest as well as post-harvest technologies is required.

Contents

1. Introduction . . . 1
2. Mass production of edible insects/processing technologies . . . 3
3. Safety aspects . . . 5
4. Nutritive value . . . 5
5. Insects as feed . . . 7
6. Insect products in food . . . 7
7. Environmental aspects . . . 8
8. Conclusions and future recommendations . . . 9
References . . . 9

1. Introduction

Entomophagy, i.e. the eating of insects, is exercised traditionally in 113 countries all over the world (MacEvilly, 2000) and more than 2,000 insect species that are considered edible have been counted to date (Jongema, 2012). The number of species eaten per country as derived from literature is shown in Table 1. It becomes apparent that the knowledge of entomophagy has been lost in the industrialized countries. Little data can be found about the eating of insects in Europe today. It has been reported that five insects or their products have been consumed in the Southern Alps of North-East Italy until about 30 years ago (Dreon & Paoletti, 2009).

The class of insects belongs just like the crustaceans (e.g. shrimp, crab, lobster, krill) to the arthropods and counts more than a million species. Insects are further divided into orders such as coleoptera (true beetles), diptera (flies), hemiptera (bugs), homoptera (tree hoppers), hymenoptera (wasps, bees, ants), isoptera (termites), lepidoptera (butterflies and moths), orthoptera (grasshopers, locusts, crickets) (Capinera, 2008). Regarding the life cycle of insects it is divided into holometabolous insects undergoing a true metamorphosis from

* Corresponding author. Tel.: +49 331 5699 613; fax: +49 331 5699 849.
E-mail addresses: brumpold@atb-potsdam.de (B.A. Rumpold), oschlueter@atb-potsdam.de (O.K. Schlüter).

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Table 1
Number of edible species eaten in different countries and regions of the world.

Region	# Edible species	Source
Africa	524	Ramos-Elorduy (1997)
Africa	246	van Huis (2003)
Angola	4	Ramos-Elorduy (1997)
Central African Republic	185	Ramos-Elorduy (1997)
Central African Republic	26	Ramos-Elorduy (1997)
Central African Republic	41	Ramos-Elorduy (1997)
Congo	30	DeFoliart (1997)
Madagascar	22	DeFoliart (1997)
South Africa	15	Ramos-Elorduy (1997)
South Africa	36	DeFoliart (1997)
Zaire	35	Ramos-Elorduy (1997)
Zaire	4	Ramos-Elorduy (1997)
Zaire	31	Ramos-Elorduy (1997)
Zaire	51	Ramos-Elorduy (1997)
Zaire	19	Ramos-Elorduy (1997), Ramos-Elorduy et al. (1997)
Zaire	62	DeFoliart (1997)
Zambia	33	Ramos-Elorduy (1997)
Zimbabwe	16	Ramos-Elorduy (1997)
Zimbabwe	32	DeFoliart (1997)
Americas		
Brazil	23	DeFoliart (1997)
Colombia	48	DeFoliart (1997)
Ecuador	83	Onore (1997)
Oaxaca, Mexico	78	Ramos-Elorduy et al. (1997)
Mexico	545	Ramos-Elorduy (2008)
USA	69	DeFoliart (1997)
Asia		
Burma	17	DeFoliart (1997)
China	46	DeFoliart (1997)
India	24	DeFoliart (1997)
Irian Jaya, New Guinea, Indonesia	>39	Ponzetta and Paoletti (1997)
Java, Indonesia	8	Lukiwati (2010)
Papua, New Guinea, Indonesia	>95	Ramandey, Mastrigt, and van Mastrigt (2010)
Indonesia	48	Ramos-Elorduy (1997)
Indonesia	25	DeFoliart (1997)
Japan	119	Ramos-Elorduy (1997)
Japan	27	DeFoliart (1997)
Laos	21	Boulidam (2010)
Sabah, Borneo (Malaysia)	>60	Chung (2010)
North-East India	81	Chakravorty, Ghosh, and Meyer-Rochow (2011)
Philippines	11	Adalla and Cervancia (2010)
Philippines	21	DeFoliart (1997)
Sri Lanka	33	Nandasena, Disanayake, and Weeratunga (2010)
Thailand	15	Leksawasdi and Paitoon (2010)
Thailand	36	Ramos-Elorduy (1997)
Thailand	80	DeFoliart (1997)
Thailand	194	Sirimungkararat et al. (2010)
Vietnam	24	DeFoliart (1997)
Oceania		
Australia	40	Ramos-Elorduy (1997)
Australia	21	Meyer-Rochow and Changkija (1997)
Australia	49	DeFoliart (1997)
Papua New Guinea	39	Meyer-Rochow (1973)
Papua New Guinea	34	DeFoliart (1997)
New Zealand	4	Meyer-Rochow and Changkija (1997)
Europe		
Italy	5	Dreon and Paoletti (2009)
World	>2.000	Jongema (2012)

egg or embryo to larva to pupa to adult and hemimetabolous insects undergoing an incomplete metamorphosis from egg to nymph to adult (Capinera, 2008).

In comparison to conventional livestock in general, insects have a higher feed conversion efficiency (Nakagaki & Defoliart, 1991) i.e. need less amount of feed for the production of 1 kg biomass, have a higher fecundity (e.g. the common house cricket lays up to 1,500 eggs over a period of about a month (Nakagaki & Defoliart, 1991)), are mostly omnivorous and can be raised on organic waste, equally nutritious and take up less space in the rearing process. It has even been indicated that insects might contribute less greenhouse gases than pig and cattle (Oonincx et al., 2010). For an industrial mass production of insects, automation technologies as well as safety procedures have to be developed to ensure an economic production process of safe food and feed products derived from insects. In addition, the consumer acceptance has to be improved. Barriers to consumption of edible insects can be overcome and food habits can be changed analogous to the ignored and partly unpublished insights of the psychologist Kurt Lewin who succeeded in encouraging U.S. citizens to include organ meats in their diet in the framework of a protein shortage during World War II by the so-called group decision method (Lewin, 1943; Wansink, 2002).

2. Mass production of edible insects/processing technologies

Although the majority of edible insects are collected in the wild up to today (Laos, 2010), the rearing of insects has been practiced for at least 7,000 years e.g. for the sericulture (silk), the production of shellac and later on also for apiculture (honey) and for the production of medicinal products. In 1936 the first mass production of a screwworm in a factory on an artificial diet had been accomplished paving the way for the sterile insect technique (SIT). A lot of research has been conducted and progress made regarding the development of artificial diets and the mass rearing of insects as biological weapons for various pest control programs since then (Singh, 1994; Singh & Moore, 1985).

The up to now uncontrolled and unsustainable harvesting in the wild leads to overcollecting, forest destruction, and extinction of species (Schabel, 2010). For marketing edible insects on an industrial scale while preserving the forests it is therefore preferable to establish cost-effective but safe farming systems of edible insects. A schematic process for the production of ready-to-eat and easy-to-prepare food and feed products derived from insects is shown in Fig. 1.

Due to a high necessity for manual labor up to now, the mass production of edible insect protein in Europe is expensive and its price is comparable to meat. For example in the Netherlands, 50 g of freeze-dried mealworms are sold for 4.85 € plus shipping costs (seen on May 30th, 2012 on http://www.webpoelier.nl/) and is advertised as amounting to 150 g if rehydrated in the cooking process. Consequently, the mealworms cost 32.33 €/kg based on rehydrated weight. In Nigeria, the caterpillar *Cirina forda* is the most widely marketed edible insect in the country and sells for about twice the price of beef (DeFoliart, 1999).

By contrast, Nakagaki and Defoliart (1991) compared different diets for rearing the domestic house cricket *Acheta domesticus* as a novelty food and calculated feed costs per kg cricket produced to be 0.21–2.55$ (wet weight; around 0.17–2.05 €) whereas crickets were sold for 30–60$/kg (24–48 €/kg) as pet feed or fish bait. This appears to be a wide profit margin. However, the manual labor, facilities and resources required for rearing the crickets had not been taken into account.

In order to make the mass production besides the purchase and consumption of insects more attractive as well as more competitive with regard to meat, it is therefore necessary to develop rearing and harvest as well as post-harvest processing technologies including safety and quality monitoring for the automation of insect (protein) production to decrease its production costs and ensure food and feed safety.

For a maximum meat and/or protein yield, a suitable edible insect species to be raised has to be selected, in doing so also the consumer acceptance (human or animal) has to be taken into consideration. Candidate insects are selected based on their size, social behavior, safety, epidemic tendencies, reproductive and survival potential, nutritional benefits, potential for storage, and marketability (Schabel, 2010). It is aimed for a high egg production, high egg hatchability, short duration of larval stage, optimum synchronization of pupation, high weight larvae or pupae, a high productivity i.e. high conversion rate and high potential of biomass increase per day, low feed costs, low vulnerability for diseases, ability to live in high densities, and a high quality protein. Depending on the species to be reared and the current developmental stage of the insect`s life cycle specific feeding might be required. Other factors influencing the rearing process include temperature, light/illumination, humidity, ventilation, rearing container properties, larvae/population density, oviposition site, food and water availability, food composition, food quality as well as microbial contamination (Peters & Barbosa, 1977; Scriber & Slansky, 1981; Sharaby, Montasser, Mahmoud, & Ibrahim, 2010; Singh, 1982; Tchuinkam et al., 2011; Vantomme, Mertens, Van Huis, & Klunder, 2012). These rearing conditions need to be controlled throughout the rearing process along the production chain (see Fig. 1). Caterpillars have been recommended as prime candidates since they are coldblooded and wingless and convert plant biomass to animal biomass 10 times more efficient than cattle and on much less land (Schabel, 2010). Furthermore, the farming of orthoptera (grasshoppers, locusts, and crickets) as food and feed has been suggested. A laboratory based study on the farming of the grasshopper *Oxya fuscovittata* resulted in a production of 1 kg of biomass in 29–35 days by 84 females (Haldar, Das, & Gupta, 1999). Due to an expected increasing demand in edible crickets the government of Lao

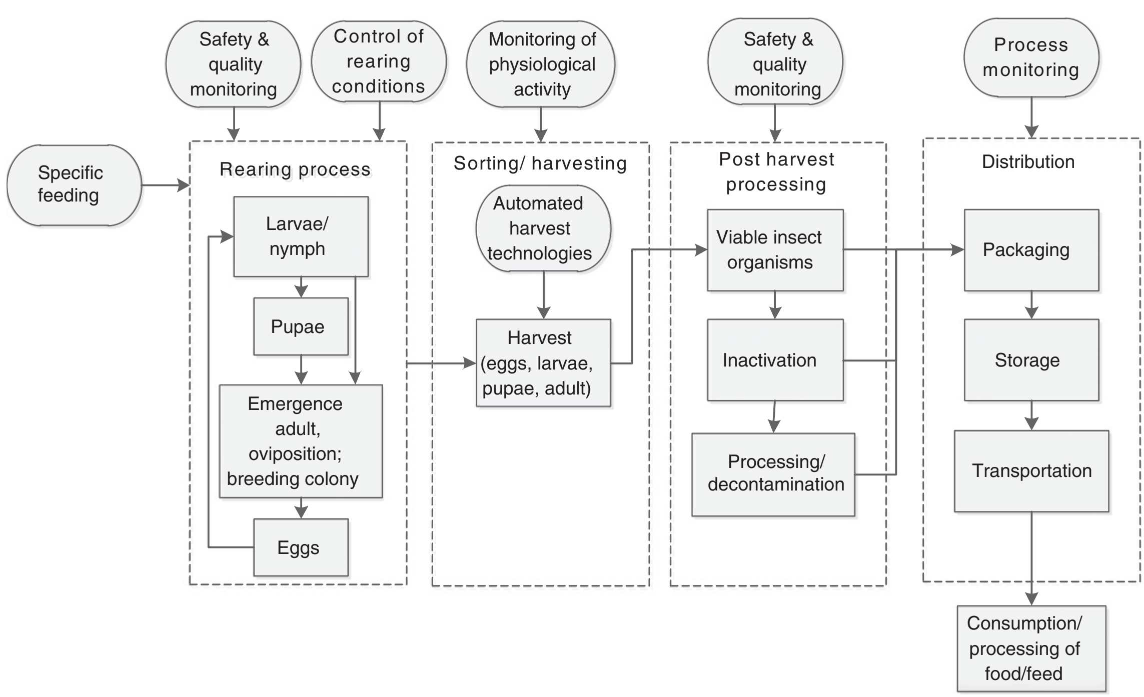

Fig. 1. Schematic production process of food and feed derived from edible insects.

Table 2
Nutrient, fatty acid, mineral, and vitamin composition of five edible insect species (based on dry matter).

(based on dry matter)	Coleoptera (beetles)	Lepidoptera (butterflies, moths)		Orthoptera (crickets, grasshoppers, locusts)	
	Rhynchophorus phoenicis (larvae)[1–7]	Bombxy mori (pupae)[8–11]	Cirina forda Westwood (larvae)[1,12–15]	Acheta domesticus (adults)[16–18]	Ruspolia differens (brown; adult)[19]
Nutrient composition					
Protein [%]	10.33–41.69	48.70–58.00	20.20–74.35	64.38–70.75	44.30
Fat [%]	19.50–69.78	30.10–35.00	5.25–14.30	18.55–22.80	46.20
Fibre [%]	2.82–25.14	2.00	1.80–9.40		4.90
NFE [%]	5.49–48.60	1.00	2.36–66.60	2.60	
Ash [%]	2.54–5.70	4.00–8.60	1.50–11.51	3.57–5.10	2.60
Energy [kJ/kg]	20,038–20,060.63	23,236.74	15,030.61	19,057.89	
% Fatty acids					
Palmitic acid (C16:0)	32.40–36.00	22.77–26.20	13.00		32.10
Staeric acid (C18:0)	0.30–3.10	4.50–7.00	16.00		5.90
SFA total	38.90–40.90	28.80–33.20	31.60		39.10
Palmitoleic acid (C16:1n7)	3.30–36.00	0.60–1.70	0.20		1.40
Oleic acid (18:1n9)	30.00–41.50	26.00–36.90	13.90		24.90
MUFA total	43.40–66.60	26.61–36.90	14.90		26.30
Linoleic acid (18:2n6)	13.00–26.00	4.20–7.30	8.10		29.50
Linoleic acid (18:3 n3/6)	2.00–3.50	27.70–38.02	45.50		4.20
PUFA total	17.70–28.00	29.90–43.92	53.80		33.80
SFA/(MUFA+PUFA)	0.43–0.64	0.40–0.50	0.46	0.56	0.65
Minerals [mg/100 g]					
Calcium	54.10–208.00	158.00	7.00–37.20	132.14–210.00	24.50
Potassium	1,025.00–2,206.00		47.60–2,130.00	1,126.62	259.70
Magnesium	33.60–131.80	207.00	1.87–69.89	80.00–109.42	33.10
Phosphorous	352.00–685.00	474.00	45.90–1.090.00	780.00–957.79	
Sodium	44.80–52.00		44.40–210.00	435.06	121.00
Iron	14.70–30.80	26.00	1.30–64.00	6.27–11.23	229.70
Zinc	26.50–15.80	23.00	4.27–24.20	18.64–21.79	13.00
Manganese	0.80–3.50	0.71	7.00–10,163.10	2.97–3.73	12.40
Copper	1.60	0.15		0.85–2.01	2.50
Selenium	1.60	0.15		0.60	0.50
Vitamins					
Retinol [μg/100 g]	11.25		2.99	24.33	2.80
α-Tocopherol [IU/kg]				63.96–81.00	22.64
Ascorbic acid [mg/100 g]	4.25		1.95	9.74	0.1
Thiamin [mg/100 g]	3.38			0.13	n.d.
Riboflavin [mg/100 g]	2.21–2.51		2.21	11.07	1.4
Niacin [mg/100 g]	3.36	0.95		12.59	2.4
Pantothenic acid [mg/100 g]				7.47	
Biotin [μg/100 g]				55.19	
Folic acid [mg/100 g]				0.49	0.9

NFE – nitrogen-free extract (i.e. carbohydrates).
SFA – saturated fatty acids.
MUFA – monounsaturated faty acids.
PUFA – polyunsaturated fatty acids.
Sources:
1 - Banjo, Lawal, and Songonuga (2006), 2 - Bukkens (1997), 3 - Ekpo, Onigbinde, and Asia (2009),
4 - Elemo, Elemo, Makinde, and Erukainure (2011), 5 - Omotoso and Adedire (2007), 6 - Onyeike, Ayalogu, and Okaraonye (2005),
7 - Opara et al. (2012), 8 - Pan, Liao, Zhang, Dong, and Wei (2012), 9 - Ramos-Elorduy et al. (1997), 10 - Rao (1994),
11 - Tomotake, Katagiri and Yamato (2010), 12 - Agbidye et al. (2009)13 - Akinnawo and Ketiku (2000),
14 - Omotoso (2006), 15 - Osasona and Olaofe (2010), 16 - Barker et al. (1998), 17 - Finke (2002), 18 - Finke (2007),
19 - Kinyuru, Kenji, Muhoho, and Ayieko (2010)

PDR proposed a regional standard to ensure food safety at the 17th session of the CCASIA (Laos, 2010). The cricket *Acheta domesticus* contains high quality proteins (Finke, Defoliart, & Benevenga, 1989), is omnivorous and easily raised. In Laos it is commonly bred on small scales (100–500 kg/year) by families as an additional source of income. Cylindrical tanks covered with mosquito nets are used as rearing containers and usually chicken feed and vegetable materials are fed (Laos, 2010). Parajulee, DeFoliart, and Hogg (1993) developed a mass rearing system for *Acheta domesticus* as food and resulted in a production model that provided a harvest of 6,000 crickets per day using 32 rearing cages ($50 \times 44 \times 20.5$ cm^3). At an estimated wet weight of 0.41–0.46 g per cricket (Nakagaki & Defoliart, 1991) this amounts to a daily production of 2.4–2.7 kg of crickets. Up-scaling is necessary since mass production of edible insects had been defined as the production of 1 t/day on the FAO technical consultation meeting in 2012 (Vantomme et al., 2012).

In order to reduce costs in the production process of edible insects, the development of automation technologies for rearing, harvesting and processing as well as distribution are necessary. This could include novel surface decontamination techniques for rearing containers as well as insects and eggs, development of monitoring devices e.g. for disease monitoring and controlled feeding units, mechanical removing systems of dead or potentially infected animals, development of continuous rearing systems e.g. on belt conveyors, automatic harvest devices, processing units e.g. for mechanical removal of wings and legs (and head), separation of protein, chitin removal, removal of the chitinous exoskeleton e.g. by high pressure processing analogue to shucking lobsters or shrimps (Jabbour & Hognason, 2011), which has simultaneously antimicrobial and anti-enzymatic impacts (Knorr et al., 2011), and process monitoring throughout distribution such as control of packaging, storage and transportation conditions.

Further means for the cost reduction include the development of cheap rearing substrates e.g. from organic waste, and the improvement and automation of sanitation procedures for the management of diseases and the reduction of losses (Vantomme et al., 2012). In addition to loss reduction during the rearing process, sanitation procedures decrease microbial contamination and consequently increase the food and feed safety.

3. Safety aspects

Not all insects are safe to eat. Just as it applies for plant and animal food products some insects are not edible or cause allergic reactions (Yen, 2010). For example, the pupae of the African silkworm (*Anaphe venata*) contain a thiaminase and can cause thiamine deficiency. In Nigeria, *Anaphe venata* is responsible for a seasonal ataxic syndrome every year for the last 40 years (Nishimune, Watanabe, Okazaki, & Akai, 2000). Some insects even contain repellant or toxic chemicals as a defense mechanism. And insects harvested in the wild that are usually safe to eat contain pesticides when they have fed in pesticide-treated areas.

All these health risks can be prevented by the consumption of common edible insect species reared on pollutant-free feed. For all insects either harvested in the wild or on farms proper processing, handling, and storage are required in order to prevent contamination and spoilage and to ensure food and feed safety.

Cases of botulism, parasitoses, and food poisoning e.g. due to aflatoxins caused by entomophagy have been reported (Schabel, 2010) and the zoonotic risk of insects in general demands attention. A direct zoonosis from insects to humans comparable to the bovine tuberculosis, influenza A (so-called bird flu) or salmonellosis is unknown but insects often transmit zoonotic agents, e.g. bacteria, viruses,parasites, and fungi, as vectors (Kruse, Kirkemo, & Handeland, 2004). Therefore contact of edible insects with infected humans or animals has to be inhibited for the prevention of zoonoses.

Investigating the microbial contamination of edible insects, *Escherichia coli* and *Klebsiella aerogenes* have been identified in freshly harvested and *Staphylococcus* sp. In heat-processed palm grubs (*Rhynchophorus* phoenicis) collected in Nigeria. The contamination of heat-processed palm grubs has mostly been attributed to improper processing and handling by healthy carriers of *Staphylococcus* sp. (Opara, Sanyigha, Ogbuewu, & Okoli, 2012). Microorganisms isolated from the gut as well as body surface of the domestic housefly larvae *Musca domestica* cultured on fresh fish included the pathogenic *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Aspergillus tamarii*, and *Bacillus cereus* and non-pathogenic *Bacillus subtilis* and *Stroplococcus faecalis* (Banjo, Lawal, & Adeduji, 2005). Similar observations have been reported for the microflora isolated from the gut as well as body surface of the larvae of the African rhinoceros beetle (*Oryctes monocerus*) collected in Nigeria, where pathogenic organisms such as *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Bacillus cereus* and non-pathogenic such as *Bacillus subtilis* and *Bacillus firmus* had been found (Banjo, Lawal, & Adeyemi, 2006). The presence of pathogenic microorganisms in insects used for food and feed pose a potential health threat that has to be overcome by processing, handling and storage measures subsequent to harvest.

Klunder, Wolkers-Rooijackers, Korpela, and Nout (2012) investigated the microbiological aspects of three fresh, processed and stored whole edible insects. In fresh insects they found rather high levels of microorganisms and levels of sporeforming bacteria and Enterobacteriaceae that were typical for fresh food harvested from the soil. Subsequent boiling (5–10 min) prevented enzymatic processes such as black discoloration of house crickets and resulted in a decrease of the microbial load and elimination of Enterobacteriacea in all insect species whereas roasting (10 min) did not completely eliminate Enterobacteriacea. Generally, the heat treatments investigated (roasting for 10 min; boiling for 5–10 min) did not entirely inactivate bacterial spores. Therefore sporeforming bacteria pose a potential risk in entomophagy and demonstrate the demand for thorough and possibly innovative decontamination techniques, e.g. high pressure thermal sterilization (Reineke et al., 2012) or conventional sterilization at 110–150 °C (van Boekel et al., 2010), and proper storage conditions. Crushing of mealworm larvae increased the overall counts of viable bacteria which indicated a release of microbiota from the gut. It is noteworthy that crushing prior to roasting or boiling did not improve the efficiency of the thermal treatment steps, respectively, but on the contrary resulted in a higher microbial load in comparison to whole mealworm larvae. In storage tests, fresh and heat treated (100 °C, 1 min) house crickets (*Acheta domesticus*) were stored at 5–7 °C and at 28–30 °C (ambient temperature in Lao PDR). Since fresh crickets had a rather high initial microbial load and even stored at 5–7 °C showed losses in sensory quality such as black discoloration, a blanching step for 1 min was recommended. Boiled crickets stored at 28–30 °C spoiled rapidly whereas stored at 5–7 °C showed a shelf life of more than 2 weeks. Drying and acidification subsequent to the boiling step could potentially increase the shelf life of house crickets stored at ambient temperature (Klunder et al., 2012).

Because the perseverance of the gut microbiota to heat treatments poses a potential microbial risk it should be investigated whether it is possible to positively influence the gut microbiota via dietary ingredients as observed for broilers where the consumption of prebiotics inhibited the colonization of enteropathogens such as *Clostridium* spp. and *Salmonella* spp. (Rehman, Vahjen, Kohl-Parisini, Ijaz, & Zentek, 2009). However, the composition of the intestinal microbiota cannot be affected by dietary shifts for every insect species. Andert, Marten, Brandl, and Brune (2010) observed no effect of different soils as diet on the intestinal microbiota of larvae of the scarab beetle (*Pachnoda* spp.).

Nevertheless, the investigations of the microbial contamination of edible insects as well as of the native intestinal microbiota illustrate the potential microbial threat of entomophagy and urge that the decontamination methods and shelf life stability of each edible insect product need to be ensured in order to obtain marketability and food and feed safety.

This is also addressed in a proposal “Development of a Regional Standard for Edible Crickets and Their Products” (CRD 8), prepared by Lao PDR as a discussion paper on the 17th session of the FAO/WHO CCASIA (Laos, 2010) in which the establishment of a standard for house crickets (or other edible insect products) for human consumption is postulated in order to protect the consumers` health and ensure quality, food safety and fair practices in food trade. The proposed standard is to include specifications of the product, standards on microbiological properties, chemical residues and contaminants, methods of sampling and analysis, packaging, preservation and storage methods as well as labeling requirements. Emphasis is put on the little knowledge on trade, the lack of legislation, and too little research in the field of food safety of edible insects in comparison to their nutritional properties and benefits.

4. Nutritive value

Numerous articles have been published addressing the nutritive value and nutrient composition of various insects. In general, edible insects were found to be good sources of proteins, fat, energy, vitamins and minerals. The consumption of 100 g of caterpillars, for example, provides 76% of the daily required amount of proteins and almost 100% of the daily required amount of vitamins for humans (Agbidye, Ofuya, & Akindele, 2009) and three silkworm pupae are supposed to

Table 3
Overview of amino acid spectra of selected edible insects in comparison to amino acid requirements in human nutrition [mg/g protein].

[mg/g protein]	his	Ile	leu	lys	meth	cys	meth + cys	phe + tyr	thre	tryp	val
Lepidoptera (butterflies, moths)											
Imbrasia epimethea (caterpillar) [1]	19.7	28.6	81.0	74.2	22.4	18.7	41.1	140.0	48.0	16.0	102.0
Usta terpsichore (caterpillar) [1]	n.d.	108.7	91.3	91.0	11.3	12.9	24.2	88.9	50.8	6.6	75.8
Bombyx mori (silkworm larvae) [2,3]	25.8–29.5	32.3–33.0	48.9–52.7	47.3–50.0	12.5–14.0	8.6–9.1	21.6–22.6	60.2–62.5	28.4–31.2	6.8–7.5	39.8–40.9
Bombyx mori (silkworm pupae) [4,5]	27.0–35.4	34.0–46.1	62.0–70.6	61.0–77.2	34.0	14.0	36.3–48.0	102–122	39.0–45.3	15–19	47.0–52.2
Galleria mellonella (waxworm larvae) [2,3]	22.4–23.4	41.6–44.7	70.8–87.9	56.0–57.1	15.6–27.3	7.8–13.0	23.4–40.4	91.3–100	36.0–41.8	8.5–8.7	48.2–54.0
Orthoptera (crickets, locusts)											
Acheta domesticus (nymphs) [2,3]	22.1–25.7	40.6–42.9	72.6–95.5	53.9–62.3	13.0–15.4	8.4–9.1	21.4–24.6	83.1–94.9	35.7–38.9	5.2–6.3	49.4–60
Acheta domesticus (adult crickets) [2,3]	22.7–23.4	36.4–45.9	66.7–100	51.1–53.7	14.6–19.6	8.3–9.8	22.9–29.3	74.2–80.5	31.1–36.1	6.3–7.6	48.4–52.2
Coleoptera (beetles)											
Tenebrio molitor (mealworm larvae) [2]	31.6	50.3	106.4	54.5	12.8	8.6	21.4	109.8	41.8	8.0	58.8
Rhynchophoris phoenicis (palm weevil larvae) [1,6]	11.0	24.0–77.5	47.0–58.9	42.0–63.9	12.0–21.0	10.6–25.0	22.6–46.0	46.4–125.0	28.6–29.0	5.1	41.0–54.9
Isoptera (termites)											
Macrotermes bellicosus (termites) [1]	51.4	51.1	78.3	54.2	7.5	18.7	26.2	74.0	27.5	14.3	73.3
Hymenoptera (bees, wasps, ants)											
Atta mexicana (ants) [7]	25.0	53.0	80.0	49.0	34.0	n.d.	n.d.	88.0	43.0	6.0	64.0
Bee brood [8]	23.4	45.7	70.2	61.7	21.3	21.3	42.6	78.7	33.0	9.6	52.1
Amino acid requirement in human nutrition[9]	15.0	30.0	59.0	45.0	16.0	6.0	22.0	30.0	23.0	6.0	39.0

His – histidine, Ile – Isoleucine, leu – leucine, lys – lysine, meth – methionine, cys – cysteine, phe – phenylalanine, tyr – tyrosine, thre – threonine, tryp – trptophane, val – valine.
n.d. – not determined.
Sources:
1 – Bukkens (1997).
2 – Finke (2002).
3 – Finke (2007).
4 – Tomotake et al. (2010).
5 – Yhoung-aree (2010).
6 – Elemo et al. (2011).
7 – Deguevara, Padilla, Garcia, Pino, and Ramos-Elorduy (1995).
8 – Finke (2005).
9 – WHO (2007).

be as rich in nutrients as one chicken egg (Mitsuhashi, 2010). Dried silkworm pupae are composed of about 50% proteins and 30% lipids (Mitsuhashi, 2010). Furthermore, a whole Bee comb approximates to being the ultimate food regarding calories and the composition of carbohydrates, proteins, fats, minerals, and vitamins (Schabel, 2010). An exemplary overview of the nutrient and fatty acid composition as well as vitamin and mineral contents of five insect species is given in Table 2.

Comparing 100 g of insect with 100 g of meat (fresh weight), its energy content is similar – except for pork due to its extremely high fat content (Sirimungkararat, Saksirirat, Nopparat, & Natongkham, 2010). However, termites, grasshoppers, caterpillars, weevils and houseflies are better protein sources by weight in comparison to beef, pork, chicken and lamb (Srivastava, Babu, & Pandey, 2009). Regarding the protein quality, it was observed that the protein of the house cricket *Acheta domesticus* was superior to soy protein on all levels of intake when fed to weanling rats (Finke et al., 1989) and that the removal of the chitin further improves the quality of the insect protein since some of the proteins are linked to the chitin. A chitin removal via alkaline extraction resulted in an increased digestibility of bee protein from 71.5 to 94.3% (Ozimek et al., 1985).

An overview of the amino acid spectra of a selection of commonly eaten insects as cited in literature in comparison to amino acid requirements for human nutrition as stated in a WHO report (WHO, 2007) is shown in Table 3. Regarding the amino acid requirements for human nutrition, the selected insects show a high-quality amino acid profile with high contents of phenylalanine and tyrosine and generally meet the requirements except for the amino acid methionine. The only insect species completely failing to meet the requirements for the essential amino acids in this table is the rich in fat palm weevil larvae.

According to literature, average protein contents of insects amount up to 50–82% (dry weight) (Schabel, 2010). More than 60% of the dry mass of caterpillars (larvae of moths and butterflies) consists of proteins.

In comparison, crickets contain less protein but more fat (Agbidye et al., 2009). The fat content of insects generally ranges from less than 10 to over 30% fat based on fresh weight (DeFoliart, 1991) and is higher in larval and pupal stages than at the adult stage (Chen, Feng, & Chen, 2009). Isoptera (termites) and Lepidoptera (caterpillars) are among the insects with the highest fat contents (DeFoliart, 1992). Live termites provide ca. 350 kcal/100 g and are composed of ca. 23% protein and 28% fat. They are the second most eaten insects all over the world following grasshoppers (Chung, 2010). Remarkable fat contents have been reported for some Lepidoptera species e.g. the butterfly larva *Phasus triangularis* with a fat content of 77% (based on dry matter) (Ramos-Elorduy et al., 1997), the maguey grub (*Aegiale hesperiales* k) with 58.55% (based on dry matter) (Melo, Garcia, Sandoval, Jimenez, & Calvo, 2011), and the waxworm *Galleria mellonella* with 51.4–60% (based on dry matter) (Barker, Fitzpatrick, & Dierenfeld, 1998; Finke, 2002, 2007) and for some Coleoptera species e.g. the palm weevil larvae (*Rhynchophorus phoenicis*) with up to 52.4–62.1% (based on dry matter) depending on the developmental stage (Omotoso & Adedire, 2007), *Scyphophorus acupunctatus* with 52% (based on dry matter) and *Oileus rimator* with 47% (based on dry matter) (Ramos-Elorduy et al., 1997). Regarding the fatty acid spectra of edible insects, the ratios of saturated fatty acids (SFA) to unsaturated fatty acids range from 0.4 to 0.65 (see Table 2).

Concerning the content of micronutrients of insects, it can generally be stated that the majority of insects show high amounts of potassium, calcium, iron, magnesium (Schabel, 2010), and selenium (Finke, 2002). Especially termites are high in iron (Banjo, Lawal, &

Songonuga, 2006; Christensen et al., 2006) and insects partially contain much more iron and calcium than beef, pork and chicken (Sirimungkararat et al., 2010). It is noteworthy that especially caterpillars generally provide many of the required minerals in abundance (Schabel, 2010). For example, a 100 g of caterpillars on average supply with 335% of the minimum daily required amount of iron (DeFoliart, 1992). In addition to iron, insects are rich in zinc (DeFoliart, 1992). It was therefore suggested that the consumption of insects could decrease iron and zinc deficiency in developing countries (Christensen et al., 2006). Furthermore, insects provide with several vitamins. For example, Bee brood is rich in vitamin A and D, caterpillars are especially rich in Vit B1, B2 and B6 (Schabel, 2010).

Regarding the high nutritional value of insects, it has to be considered that the nutrient profile of insects is highly dependent on the feed composition. For example, feeding mealworm larvae on different diets containing organic wastes resulted in different nutrient compositions of the larvae (Ramos-Elorduy, Gonzalez, Hernandez, & Pino, 2002). Most of the nutrient compositions of insects specified earlier have been derived from insects collected in the wild. If organic waste is utilized for the industrial farming of insects the resulting nutrient profile of the insects ought to be contemplated. In addition to the nutrient profile, the presence of potentially harmful ingredients such as allergens should be investigated to ensure safe food and feed products.

5. Insects as feed

Insects have a great potential as feed especially taking into account their nutritional value, low space requirement, and the great acceptance of particularly poultry and fish as well as reptiles since insects belong to their diet in their natural habitat. In addition to that insects used for feed can be raised on organic wastes such as manure and fish offal without evoking revulsion and ethical issues. Furthermore, termites could be utilized for the degradation of wood waste while functioning as feed (Mitsuhashi, 2010). Termites are the second most eaten insect all over the world and are rich in fat and proteins (Chung, 2010).

Acridids (grasshoppers) have been identified as one potential feed component for poultry feed since they have higher protein contents than other protein sources such as soybean meal and fish meal and are rich in the micro-nutrients Ca, Mg, Zn, Fe, and Cu (Anand, Ganguly, & Haldar, 2008). In the Philippines, grasshoppers are fed to chickens raised on pasture. These chicken fed on pasture (and grasshoppers) are to have a delicious taste and are sold for a much higher price than chickens reared on commercial chicken feed (Litton, 1993).

Investigating the dietary potential of the moth larvae *Cirina forda* as a poultry feed component rich in proteins in comparison to fish meal, a complete replacement of the fish meal by larvae powder resulted in no significant differences in growth rate and weight gain of broiler chicks (Oyegoke, Akintola, & Fasoranti, 2006). Thus the larvae powder represents a potential alternative for the highly nutritious and rather expensive fish meal. It is also feasible to replace fish meal with dried silkworm pupae *Bombyx mori L.* meal in poultry rations with regards to growth and egg production (Wijayasinghe & Rajaguru, 1977). In these feeding trials the silkworm pupae has been ground and manually separated from chitinous matter (54%) which is not satisfactory from an economical point of view.

Supplementing chick feed with 10–15% of housefly larvae yielded in improved growing performance and carcass quality of broiler chicks. In the breast muscle of the chicks the protein content remained constant whereas its lysine and tryptophan content increased. This had been attributed to the optimal amino acid profile, high protein content of 63.99% dry weight, or high protein digestibility of 98,5% of the larvae (Hwangbo et al., 2009). Dried housefly pupae and dried house flies grown on chicken manure and fed to chicks could completely replace soybean meal as a protein source with regard to weight gain and feed conversion rate (Calvert, 1979).

In addition to functioning as a protein rich feed supplements for poultry, house fly larvae are applied to reduce poultry waste because they are able to convert poultry manure into biomass (Calvert, 1979; El Boushy, 1991; Hwangbo et al., 2009). In addition, the black soldier fly can be utilized to reduce manure waste of laying hens by more than 50% while at the same time serving as feed and reducing costs for fly control and manure removal (Sheppard, Newton, Thompson, & Savage, 1994). Besides chicken manure the black soldier fly has also been successfully reared on swine and cow manure as well as fish waste (Sealey et al., 2011; St-Hilaire, Cranfill, et al., 2007; St-Hilaire, Sheppard, et al., 2007).

Furthermore other organic wastes can be utilized for the feed production via insects. The mealworm larvae *Tenebrio molitor* had been reared on organic wastes, e.g. derived from fruit and vegetable processing, dried and mixed in a diet containing 19% protein for broiler chicken. The feeding trials showed no significant differences in feed uptake, weight gain, and feed efficiency for the feed containing 0, 5 and 10% mealworm larvae, respectively, which makes *Tenebrio molitor* reared on organic waste a potential supplement for chicken feed (Ramos-Elorduy et al., 2002).

Finke et al. (1989) evaluated the protein quality of different insect meals fed to weanling rats and observed that proteins from both cricket meals tested were equal or superior to soy protein as an amino acid source for rats.

It has to be investigated whether insects have the potential to replace or at least decrease the amount of fish meal and fish oil in fish feed considering the lack of polyunsaturated omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in the fatty acid profiles of insects.

Partly replacing fish meal and fish oil with black soldier fly pupae reared on swine manure and housefly pupae reared on cow manure while maintaining crude protein and crude fat contents resulted in rainbow trout with comparable feed conversion ratio but reduced levels of the omega-3 fatty acids EPA and DHA (St-Hilaire, Sheppard, et al., 2007).

Partly replacing protein of fish meal with black soldier fly prepupae reared on cow manure and enriched black soldier fly prepupae that had additionally been fed fish offal in the last month before harvest while maintaining amino acid profiles of the feed resulted in rainbow trout with no significant differences in feed uptake, conversion efficiency, and sensorical properties. Only the growth of trout feeding on the diet containing the fly prepupae without fish offal had been reduced in comparison to the control diet. The fatty acid profiles of the fly prepupae show EPA and DHA in the enriched black soldier fly prepupae but not in the normal black soldier fly prepupae and an increase in PUFA in general which demonstrates that insects can take up EPA and DHA and other PUFA such as α linolenic acid (ALA) with their diet (Sealey et al., 2011). Feeding black soldier fly larvae reared on cow manure and 22% of fish offal within 24 h of their pupation was sufficient for a substantial enrichment in PUFA, especially in DHA and EPA (St-Hilaire, Cranfill, et al., 2007).

Accordingly it is possible to manipulate the lipid and fatty acid content of flies and to obtain a significant enrichment in omega-3 fatty acids by feeding them fish waste as fatty acid recycling. Thus non-pest fly species could be used for the production of high quality (fish) feed rich in omega-3 fatty acids as a replacement of fish meal and fish oil while simultaneously reducing animal waste (St-Hilaire, Cranfill, et al., 2007).

6. Insect products in food

In addition to producing silk, wax and dyes and functioning as animal bait, up to today several products derived from insects are used as food ingredients or are consumed for medicinal purposes.

These include for example bee honey, food coloring (cochineal red, food dye from *Lacciferidae* and *Margarodes polonicus*) and as pharmaceuticals e.g. propolis, royal jelly and venom from bees (Schabel, 2010).

It is generally conceivable to use insects and their products as food ingredients with nutritional but also with functional benefits. Omotoso (2006) investigated the functional properties of *Cirina forda* larvae powder and particularly obtained high oil and water absorption capacities. This was in accordance with Osasona and Olaofe (2010) who also observed a high water absorption capacity and oil absorption capacity, respectively, of *C. forda* larvae powder and concluded that the larvae powder could be applied especially in baked products due to its high water absorption capacity, as a flavor retainer and to improve the mouth feel of food products because of its high oil absorption capacity. A relatively high emulsion stability and emulsion capacity suggests further that the larvae powder could function as a texturizing agent in food products (Omotoso, 2006). The foaming properties of the larvae powder were shown to be poor, the least gelation concentration of *C. forda* larvae powder was similar to least gelation concentration of bovine plasma protein concentrate (Omotoso, 2006) or rather of lupine seed (Osasona & Olaofe, 2010). Functional properties of other insects and insect proteins need to be examined for their potential application as texturizing food ingredients as well as ingredients of protein-rich meat replacing products. Its nutritional benefits notwithstanding, insect protein only qualifies as a meat replacer if it can be produced efficiently not only regarding the production costs but also regarding environmental aspects such as water and energy consumption and emissions.

7. Environmental aspects

Regarding the high protein content and the good nutrient profile of insects, it has to be considered whether edible insects could be produced to substitute meat products and also be applied as feed constituents and consequently represent a considerable alternative to conventional livestock. Accordingly the environmental impact of the mass production of insects in comparison to meat production has to be evaluated. Unfortunately little data exists up to now on the environmental impact of insect rearing.

Between 1980 and 2004 the global meat production has almost increased twofold and the trend is continuing. In developing countries the growth has been even nearly threefold with an annual growing rate of more than 5%. This trend is due to a shift in consumption habits (FAO, 2005) and results in a rapidly rising demand in feed and consequently land as well as fresh water and in an increase in green house gas production. By contrast, research indicates a decline in insect eating in many parts of the world (Gracer, 2010) which may be due to increasing urbanization and said shift in consumption habits.

Mekonnen and Hoekstra (2010) studied the global water footprints of farm animals and animal products and estimated the average water footprint for meat as 15400 l/kg beef, 6000 l/kg pork and 3400 l/kg chicken meat. Considering that the water footprint of the feed has the highest share in the water footprint of the meat production, the low energy conversion efficiency especially of cattle becomes very obvious. In order to produce 1 kg of meat, 7.7 kg feed is required for beef, 6.3 kg for sheep, 3.6 kg for pork, 2.2 kg for chicken and 1.7 kg for cricket meat (Huis, 2010). This leads to the conclusion that regarding the global water consumption as well as the rising demand in food due to an increasing world population, the consumption of plants is favorable to animal products derived from conventional livestock. Since insects have a much higher feed conversion efficiency because they are cold-blooded, are able to derive their moisture demand from food and hence not necessarily require drinking water, and can grow on organic waste, which also reduces the water footprint of the feed, it would be interesting to compare their water footprint with water footprints of animal products as well as feed crops with regard to nutritional quality. It has to be considered however, that the feed conversion efficiency of insects is temperature-dependent (Roe, Clifford, & Woodring, 1985). Reared at 25 and 35 °C, respectively, it was discovered that the last larval instar of the common house cricket *Acheta domesticus* showed higher uptakes of food and slightly lower weight gain at 25 °C, the duration of the larval stadium increased from 6 to 14 days and in addition more oxygen was consumed and more carbon dioxide produced at 25° than at 35 °C. This is in agreement with data obtained by Booth and Kiddell (2007) rearing *Acheta domesticus* at 25 and 28 °C, respectively. They observed lower mass gain per day, longer development time and twice as much energy uptake due to the longer development period at 25 °C than at 28 °C. Furthermore, they resulted in a higher adult body mass at 25 °C than at 28 °C, however.

It can be concluded that temperature-controlled rearing containers are necessary for optimum mass gain of insects at minimum time, minimum food uptake and minimum emissions which implies increased energy usage in comparison to conventional livestock.

In addition to the water consumption of food and feed production, its environmental impacts concerning the greenhouse gas production have to be taken into consideration. Regarding the global contribution of livestock on greenhouse gas emissions in general, livestock was found to be responsible for 9% of CO_2, 35–40% of CH_4, 65% of N_2O and 64% of NH_3 productions of all anthropogenic green house gas emissions (Steinfeld et al., 2006).

In a recent publication, the production of green house gases and ammonia of pigs and cattle as cited in literature and of five different insect species (mealworm *Tenebrio molitor*, *house* cricket *Acheta domesticus*, migratory locust *Locusta migratoria*, larvae of the sun beetle *Pachnoda marginata*, and Argentinean cockroach *Blaptica dubia*) have been compared (Oonincx et al., 2010). Only the first three insect species are considered edible insects, the two latter had been included as possible feed products because they are easily mass bred on various substrates. In this study it was shown that the insects investigated produced a comparable or lower amount of greenhouse gases in general and CO_2 per kg mass gain in particular than pigs and a much lower amount than cattle. The NH_3 production of all 5 insect species was lower than for livestock. Of the insects, methane emission was only observed for *Pachnoda marginata* and *Blaptica dubia* since only the insects cockroaches, termites and scarab beetles produce methane (Hackstein & Stumm, 1994). The methane production of the beetle larvae and the cockroach was comparable or slightly lower than of pigs and more than 20 times lower than of cattle (Oonincx et al., 2010). However, it has to be taken into account that the emissions of insects were only measured for a time period of 3 days and not their entire life span and only certain nymphal/larval stages had been included in the study (except for *Blaptica dubia*). It cannot be excluded that the greenhouse gas production rates vary between different developmental stages. Higher CH_4 emissions have been observed for larvae than for adults of the American cockroach *Periplaneta americana*, for example (Kane & Breznak, 1991). And it is furthermore questionable whether 3 days can be considered a representative time span. As mentioned earlier, Roe et al. (1985) investigated the impact of the rearing temperature on the energy distribution during the last larval stage of *Acheta domesticus* and detected varying mass gain, food uptake as well as carbon dioxide production per day within the stage period. In addition, a great variance between emissions from different insect species has been detected (Oonincx et al., 2010) that could be attributed to differing rearing temperatures (Roe et al., 1985), feed (Kane & Breznak, 1991; Santo Domingo et al., 1998) as well as species. It is recommended that insects for the industrial mass production should also be selected according to their environmental impact regarding greenhouse gas emissions although insects appear to be preferable to conventional livestock.

As a concluding remark on the environmental impact of entomophagy the potential decrease in the use of pesticides has to be pointed out. Controlled collecting of edible insects considered as crop pests in the wild can prevent pests and thus the need for insecticides. Taking into account the protein content of plants (up to 38% for dry soy beans (Saxholt et al., 2009)) in comparison to the protein content of e.g. grasshoppers (up to 77% based on dry weight (Ramos-Elorduy et al., 1997)) the use of pesticides for the preservation of plants in favor of grasshoppers becomes debatable. In addition, economical advantages of insect collecting instead of plant cultivation should be considered. In Thailand, a small farmer could earn up to 120 US Dollars per half acre by collecting grasshoppers in 1992, which was twice as much as he could earn from corn (DeFoliart, 1997).

8. Conclusions and future recommendations

It can generally be concluded that insects are a potential source for food and feed since they have a well-balanced nutrient profile, meet amino acid requirements for humans and livestock, are high in polyunsaturated fatty acids and generally rich in micronutrients and vitamins. Depending on their feed, insects even pose a considerable alternative to fishmeal in feed formulae. In addition to their nutritional benefits, insects need to be examined for their functional properties and their potential application as texturizing food ingredients as well as ingredients of protein-rich meat replacing products.

Appropriate species selection based on suitability for mass production and characteristics such as robustness and protein/biomass supply and on intended use is also mandatory. Additionally, appropriate low-cost feed e.g. from organic waste and by-products that preferably in addition provides with certain essential nutrients such as EPA and DHA or essential amino acids or micronutrients needs to be identified.

In comparison to livestock, rearing insects seems to be more environmentally friendly with regards to greenhouse gas production, water consumption and land requirement. More research is required and data needed on emissions, energy and water consumption of insect rearing processes to make a profound statement.

For distribution and consumption of industrially mass-produced insects as food all over the world education of the public as well as image improvement of edible insects needs to be performed in order to establish and increase consumer acceptance. Furthermore, international food regulations need to be established for food safety of insect products. In order to produce insects on an industrial scale technological improvement of rearing facilities for automated, cost-effective production processes, the development of hygienic measures and sanitary standards for the prevention of diseases and contamination throughout the rearing process as well as processing and handling steps, and the development of reliable preservation and preparation methods to ensure food and feed safety including the inactivation of gut microbiota are required.

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