



Review

Entomophagy: Nutritional, ecological, safety and legislation aspects

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ABSTRACT

Globally, there is a need to seek alternative sources of protein in addition to meat. This has led to considerable interest in edible insects. Such insects form part of cultures and diets in many Asian and African countries, and are an excellent source of essential nutrients, minerals, vitamins and proteins. Furthermore, they have been reported to be sustainable. The ecological importance of insects is related to their short life cycles when reared and farmed. This makes them ideal in mitigating greenhouse gas emissions, cutting land uses and polluted water, and reducing environmental contamination. However, the use of edible insects as food in Europe is minimal. To ensure safety of insects when eaten as food, considerations should be made on: microbiological contamination; toxicological hazards, e.g. chemical hazards and antinutrients; allergenicity issues that are related to different exposures, including injection, ingestion, inhalation and skin contact. In this review, we summarize the nutritional and sustainable values of edible insects, look at safety and legislative measures and we finally discuss future issues.

1. Introduction

Insects are consumed in many parts in the world, most prominently in regions of Latin America, Asia and Africa. This practice is considered a relevant nutrient source for the people living in these areas, and is often considered a delicacy (Feng et al., 2018; Patel, Suleria, & Rauf, 2019; Raheem et al., 2019). Besides being eaten as food, insects play many other important roles such as pest control, pollination and nutrient cycling (Dzerefos & Witkowski, 2014).

Compared to other sources of animal protein such as beef or pork, insects are a sustainable source of protein, which is why the Food and Agricultural Organization (FAO) promotes the consumption of insects, i.e. entomophagy (FAO, 2013). The production chain of animal agriculture is responsible for 9% of carbon dioxide emissions and 18% of total global human-induced emissions (Steinfeld, Gerber, Wassenaar, Castel, & de Haan, 2006). They are caused by different processes in the chain: production of the feed including its fertilization, energy,

transport of feed and animals, changes in land use, and the slaughtering and processing of meat (Alexander et al., 2017; Steinfeld et al., 2006). Methane emissions of the same chain are approximately 35–40%, while ammonia emissions are 65% (Steinfeld et al., 2006). Oonincx et al. (2010) found that insect rearing was much lower in greenhouse gas (GHG) emissions as the investigated insect species *Pachnoda marginata*, *Tenebrio molitor*, *Blaptica dubia*, *Acheta domesticus* and *Locusta migratoria* revealed that methane production levels ranged between 0.00 and 0.16 g/kg body mass/day, whereas beef cattle obtained 0.239 g/kg body mass/day. By considering the example of *Acheta domesticus*, *Locusta migratoria* and *Blaptica dubia*, the production of much small amounts of ammonia (3.0–5.4 mg/kg body mass/day) than for conventional livestock (4.8–75 mg/kg body mass/day for pigs and 14–170 mg/kg body mass/day for cattle). With less demand for feed and reduced land space for insect rearing, the issues with reducing farmlands associated with meat production will also be alleviated (Alexander et al., 2017).

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Smil (2002), as documented by Kauppi, Pettersen, and Boks (2019), reported that feed-to-meat conversion rates for the production of 1 kg of meat required 10 kg of feed for 1 kg of beef, 5 kg of feed for 1 kg of pork, 2.5 kg of feed for 1 kg of chicken. Collavo et al. (2005) indicated that 1.7 kg of feed was required to produce 1 kg of house cricket. Miglietta, De Leo, Ruberti, and Massari (2015) also reported a water footprint of 4341 m³ per ton of edible insect production, especially for mealworms (*Tenebrio molitor*), which was lower than that recorded for beef that required 154,115 m³ per ton, along with 5988 m³ per ton of pork and 4325 m³ per ton of chicken.

As of December 2018, the European Food Safety Authority (EFSA) has requested the approval of five different insect species as novel foods (European Commission, 2018), including house cricket (*A. domesticus*), yellow mealworm (*T. molitor*), migratory locust (*Locusta migratoria*), lesser mealworm (*Alphitobius diaperinus*) and tropical house cricket (*Gryllobates sigillatus*). Consequently, the EFSA has formulated a risk profile of insects as food and feed for consumers (EFSA, 2015), and that packaged insect products must be disclosed on packaging material so that consumers can know the possible allergens of packaged edible insect products (Evira, 2018). Additionally, the industries interested in commercializing edible insects are expected to make a standard food safety assessment called the Hazard Analysis Critical Control Point to be able to sell edible insects in European countries and to avoid health risks for consumers (Kauppi et al., 2019).

In Europe, the need to switch to more sustainable food production has sparked an interest in insect consumption. With its high protein content, essential fatty acids and richness of minerals, insects as a good alternative to other animal protein come from not only a sustainability viewpoint, but also from a nutritional perspective. Research into alternative protein sources is ongoing (Henchion, Hayes, Mullen, Felonon, & Tiwari, 2017) and it is estimated that 33% of the consumed protein will come from alternative sources by the year 2054, which would come to 311 million metric tons (311 MMT) of alternative protein (Populi, 2015). Insects are thought to have a market share of 11% (34 MMT) on the alternative protein market (Probst, Frideres, Pedersen, & Amato, 2015). In European and North American markets, insect as food is often met by a disgust factor. Using insects as an ingredient (i.e. powder or puree) may help overcome this perception. Following the disgust factor is legislation in Europe, which has been insufficient until 1st of January 2018. In the past, as insects were present in neither normal dietary patterns of most Europeans nor feed formulations, no legislation was necessary. The legislation that has long since been absent is now gradually being implemented and needs to be harmonized (Lahteenmaki-Uutela et al., 2017; Sogari, Amato, Biasato, Chiesa, & Gasco, 2019). The growing interest shown in insect ingredients requires suitable regulatory frameworks (FAO, 2013) to improve edible insect acceptance and to maximize market opportunities.

Insects grow fast and efficiently at a good feed-to-food conversion rate, and their life cycle is short: e.g., weeks for crickets as opposed to months for chickens and years for most ruminants. It was estimated that up to 80% of a cricket is edible and digestible compared to 55% of chicken and pigs and 40% of cattle (Nakagaki & Defoliart, 1991).

The purpose of this review article was to highlight the intertwined burden of nutrition in a climate change-challenged world. We explored the possibilities of entomophagy as a suitable alternative to meat to reduce this burden. We also suggest that quality safety measures and legislation would help to improve the overall acceptability of edible insects as food and feed. In this review, we discuss the nutritional value of edible insects in Section 2, and provide an overview of sustainability for ecological importance in Section 3. We also discuss safety issues, including allergenicity, in Section 4, and legislation in Section 5. Finally, Section 6 considers the future and offers some concluding remarks.

2. Nutrition

Malnutrition is still largely present. Worldwide, 825 million people are undernourished, especially in China and India with the largest populations (UN, 2014). Rural areas frequently show a higher malnutrition incidence than urban areas (KNBS, 2010). Even though enough calories are supplied, diet may lack major nutrients (WHO, 2007) as food in rural areas is mostly plant-based with relatively low nutrient density and low protein with a high biological value content. These foodstuffs may contain antinutritional factors, e.g. phytic acid, tannins, phenolics, etc., that limit micronutrient absorption and, thus, further deplete diet (Towo, Matuschek, & Svanberg, 2006).

Especially in the first year after birth, nutrition is essential for good health, when nutritional requirements differ from those of adults. At about 6 months of age, during the period when breastfeeding needs to be supplemented by other food, children in poor areas struggle to receive optimum nutrition (Martin, Gunnell, & Davey Smith, 2005). Many children underfed in their first year of life present growth defects (Semproli & Gualdi-Russo, 2007; Shrimpton et al., 2001). In Kenya, 35% of children aged under 5 are stunted, 7% are wasted and 16% are underweight (KNBS, 2010). The problems for this group are caused by a combination of inadequate nutrition and disease (Martin et al., 2005).

More insect consumption can be one way of helping to fight malnutrition worldwide. Huge differences exist and depend on species, developmental stages and growth conditions. As an example, the compositions of some edible insects are provided in Table 1, while variation between similar species or between growth conditions is exemplified in Table 2.

Overall, insects can generally provide satisfactory energy and proteins with a favorable amino acid composition. They are also high in

Table 1
Proximate composition of some selected traditional edible insects (g/100 g).

Insects/Parameters	From (country)	Protein (%)	Fat (%)	Dietary fibre (%)	Carbohydrate (%)	Approximate energy (kcal/100 g)
Agoro termite	Kenya	39.3 ± 0.1	44.8 ± 2.8	6.3 ± 1.1	1.8 ± 0.7	568
Sisi termite	Kenya	33.5 ± 0.8	46.5 ± 2.1	6.5 ± 0.0	8.7 ± 1.8	587
Oriwo termite	Kenya	39.7 ± 0.6	47.0 ± 1.0	6.2 ± 2.0	2.3 ± 0.9	591
Oyala termite	Kenya	37.5 ± 0.1	47.3 ± 0.1	7.2 ± 0.4	0.7 ± 0.0	579
Onyoso ant	Kenya	40.8 ± 1.1	47.5 ± 2.7	5.91 ± 1.9	0.2 ± 0.0	592
Black ants	Kenya					
Thorax		39.8	42.1	10.1	N/A	538
Abdomen		44.6	49.8	4.3	N/A	627
Whole body		40.8	40.8	6.9	N/A	530
Winged termite (<i>Macrotermes bellicosus</i>)	Nigeria	64.7	34.1	3.0	32.5	695
Rhinoceros beetles						
Oryctes monoceros	Nigeria	47.0	23.6	16.5	9.6	438
Oryctes boas	Nigeria	36.3	22.5	8.3	27.1	456

Source: Kinyuru et al. (2012), Kinyuru et al. (2013), Ayieko et al. (2012), Idowu, Oliyide, Ademolu, and Bamidele (2019).

N/A: Not available.

Table 2

Variation in nutritional value between similar samples in % on a dry weight basis.

Species	Source of variation	Protein	Fat	Carbohydrate	Fibre	Energy (kcal/100 g)
Grasshopper	Similar species	62.4–67.2	4.8–6.8	N/A	7.0–9.2	392–402
Mealworm (<i>T. molitor</i>)	Diet	44.8–50.1	39.1–40.5	0	13.8–18.8	543–552
Cricket	Supplier of powder	42.0–45.8	23.6–29.1	19.6–21.8	3.5–7.4	486–524

Source: Sun, Shang, Liu, and Long (2010), Alves, Sanjinez-Argandoña, Linzmeier, Cardoso, and Macedo (2016), Montowska, Kowalczewski, Rybicka, and Fornal (2019).

N/A: Not available

mono- and polyunsaturated fatty acids, and form a source of omega 3 fatty acids (Ghosh, Lee, Jung, & Meyer-Rochow, 2017). They are rich in a number of minerals and vitamins, particularly zinc and iron (Rumpold & Schlüter, 2013; Xiaoming, Ying, Hong, & Zhiyong, 2010; Johnson, 2010; Capinera, 2004, Banjo, Lawal, & Songonuga, 2006; Glover & Sexton, 2015; Kinyuru, Kenji, Muhoho, & Ayieko, 2010; Ayieko, Kinyuru, FNdong, & Kenji, 2012; Manditsera, Luning, Fogliano, & Lakemond, 2019a). For some species, the calories obtained per 100 g exceed 750 kcal (Pal & Roy, 2014), which is higher than soybean, corn or beef. In some countries, insects are one of the main protein sources and supply 6100 kcal per person per year, and 513 g of protein per person per year (Ramos-Elorduy, 2005). Recent research conducted on the African continent has concluded that insects form an important part of people's daily diet in northern Angola, at least during a certain season (Lautenschläger et al., 2017), and a wide variety of edible insects are consumed in both the South and North Sudanian zones of Burkina Faso (Séré et al., 2018).

Some examples of insects that are often consumed are grasshoppers, white ants and the silkworm. Grasshoppers and white ants are seen as a delicacy and are similarly priced. Despite their high price, they are an important source of protein and fat, and could, therefore, be considered to be worth growing. For feed, silkworm pupae meal is interesting for its high protein content. Its meal contains 50% protein (on a dry weight base), which increases to 80% once defatted, and it contains large amounts of lysine and methionine (respectively 6–7% and 2–3% of protein content) (Finke, 2002).

In order to benefit from the high protein content in edible insects, there is a need to acquire a more comprehensive strategy. In response to this, the newly formed North American triad of experts from academia, industry and government, the Tripartite Organization for the Promotion of Insect Consumption (TOPIC), explores the diversity of potential benefits that will result from the regular consumption of insect-based foods and the potential obstacles that hinder the creation of an expanded market (Mason et al., 2018).

2.1. Proteins

Many insect species contain large amounts of protein. Protein content is often higher than that in soybean and is similar to that of poultry and fish (Bosch, Zhang, Oonincx, & Hendriks, 2014). True protein and crude protein are nearly the same for most insect species (Finke, 2007). In Fig. 1, protein content is shown as a percentage of dry weight for some insect classes and a number of insect species versus beef and pork (Bukkens, 1997; Finke, 2004; Yhoun-Aree, 2010). As Bukkens (1997) only provided a general number for the protein content of beef and pork, some specific numbers were used to complement, taken from a food database (www.voedingscentrum.nl). The entry 'beef' contains four different beef products: steak, ground beef, low-fat ground beef and beef rib. The insects considered for consumption in the Western world, like crickets and mealworms, contain similar quantities of protein to conventional meat products. Recent research reports that the consumption of 50 g of *Eulepida Mashona* (beetle) and *Henicus whellani* (cricket) may contribute to 30% of recommended daily protein on average (Manditsera et al., 2019a). Another study conducted by

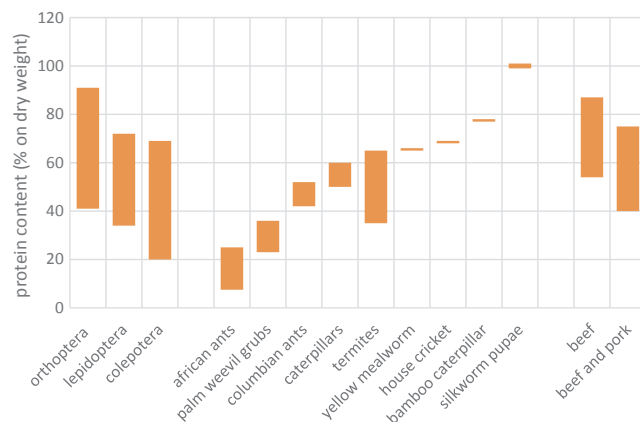


Fig. 1. Protein content of some insect classes, a number of specific insect species, compared to beef and pork. The values are reported by Bukkens (1997), Finke (2004), and Yhoun-Aree (2010) for the beef.

Manditsera, Luning, Fogliano, and Lakemond (2019b) was concluded that domestic cooking methods can influence the protein digestibility of these same insect species (*Eulepida mashona* and *Henicus whellani*). These authors found that a maximal decrease in protein digestibility was around 25%. So roasting should be preferred to boiling. In any case, short boiling times are recommended.

The essential amino acid content of insects is good. Once again, a big difference appears between insect species, but also between different samples of the same insect type. An excellent overview of a large number of edible insects can be found in Bukkens (1997), which explains that lysine and tryptophan are often the limiting factor (Bukkens, 1997). In Nigeria, four edible insect species contain all the essential amino acids, specifically methionine, threonine and lysine. Indeed the palm weevil species *R. phoenicis* has a favorable amino acid composition. *Rhynchophorus bilineatus* larvae contain large amounts of both lysine and leucine. In a diet consisting mainly of cereals and tubers (sweet potato, yam and taro), which is the case in many countries where hunger prevails, lysine deficiency often occurs. For a tuber-based diet, leucine is often short. Therefore, special attention is paid to these amino acids, which could be supplied by *R. phoenicis* or *Rhynchophorus bilineatus*. In a more recent study, bombay locusts, scarab beetles, house crickets and mulberry silkworms were compared in terms of amino acid composition (Köhler, Kariuki, Lambert, & Biesalski, 2019). House crickets and mulberry silkworms were obtained from two different sources. Fig. 2 shows essential amino acids compared to the recommended value. Most essential amino acids are present in amounts above the recommended values. Lysine is around the recommended value, and some of the samples lacked sulfur-containing amino acids, whereas Bukkens (1997) mentioned that tryptophan and lysine are often limiting. The differences between the various samples of one species (cricket and silkworm in this study) are limited (Köhler et al., 2019).

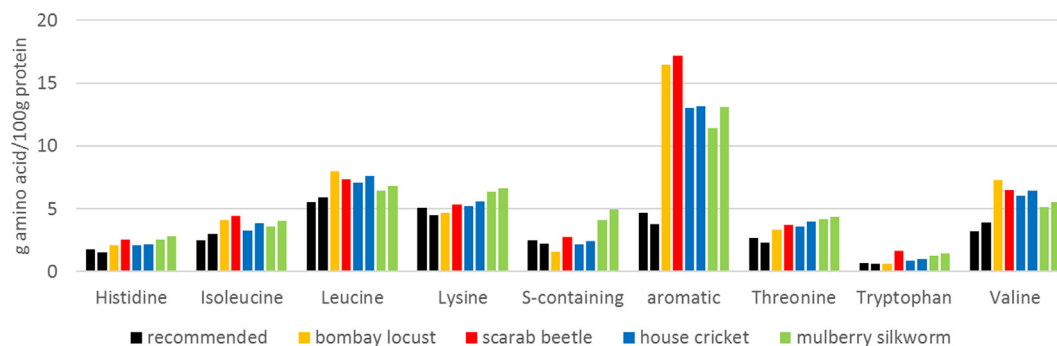


Fig. 2. Essential amino acids of four insect species (Köhler et al., 2019), compared with the recommendations (in black) from the Institute of Medicine (Trumbo, Schlicker, Yates, & Poos, 2002) and the WHO (2007).

2.2. Fats

The fat content of insect species vastly differs, as does their protein content. Fat composition differs per species (Rumpold & Schlüter, 2013) and is also influenced by the feeding of insects (Barroso et al., 2017). Termites, caterpillars and palm weevil larvae are high in fat (Bukkens, 1997; Elemo, Elemo, Makinde, & Erukainure, 2011). Most insects present a saturated/non saturated fatty acid ratio below 40% (Table 3), which is better than that observed in fish or chicken, and more polyunsaturated fatty acids like linolenic and linoleic acids are present. Given this favorable composition, the oil extracted from *Rhynchophorus phoenicis* grubs is used as edible oil (Okaraonye & Ikewuchi, 2008; Onzikou et al., 2010). Grasshoppers and white ants also have a favorable fatty acid composition, with 60% and 75% of fats being respectively unsaturated, and with a linoleic acid content of 1.4% and 6.7% and oleic acid content of 44% and 48%, both respectively. Silkworm pupae contain 20–40% fat (on a dry weight basis), with a large amount of polyunsaturated fatty acids. In fact, 11–45% of total fatty acids consist of linolenic acid (Heuze, Tran, Giger-Revedin, & Lebas, 2015).

2.3. Chitin

The exoskeleton of many insects consists of chitin. In a biorefinery of insects, chitin and its derivative chitosan are of much interest. They are claimed to have immunity-enhancing effects by inhibiting the growth of pathogenic microorganisms, while promoting the growth of beneficial bacteria (Kong, Chen, Xing, & Park, 2010). Insects contain 1–7% chitin (Finke, 2007). For example, silkworm pupae meal is relatively low, with 3–4% chitin on a dry weight basis (Finke, 2002; Suresh

et al., 2012). As chitin contains nitrogen, it influences protein estimates based on nitrogen measurements (Bosch et al., 2014).

2.4. Micronutrients

Insects are rich in micronutrients. By way of example, caterpillars and termites contain 35.5 mg iron/100g dry weight (Banjo et al., 2006) and 27–29 mg iron/100 g dry weight, respectively (Banjo et al., 2006). Grasshoppers and the giant water bug *Lethocerus indicus* contain 226–238 mg phosphorus per 100 g (Feng, Chen, Wang, Ye, & Chen, 2000). Grasshoppers and weevils comprise 7.54–8.21 mg magnesium per 100 g (Banjo et al., 2006). The dung beetle grub *Oryctes* sp. contains 61.3 mg calcium per 100 g dry weight (Banjo et al., 2006), while the palm weevil grub comprises 72.4 mg (Onzikou et al., 2010) and adult house crickets 76 mg per 100 g dry weight (Vogel, 2010). The mineral composition of a number of insects from Nigeria and Kenya are as shown in Table 4, respectively. Iron and zinc contents are especially important as these minerals are often deficient in developing countries (Manditsera et al., 2019a; Rumpold & Schlüter, 2013). A recent study concluded that the consumption of 50 g of *Eulepida mashona* and *Henicus whellani* may contribute to 30% and 50% of the recommended daily zinc and iron, respectively, on average (Manditsera et al., 2019a). Two billion people suffer zinc deficiency and one billion present iron deficiency (Banjo et al., 2006), and 25% and 17% of the world's population is vulnerable to iron deficiency and zinc deficiency respectively. Children and women of reproductive age are particularly vulnerable. Unlike the iron found in many plant sources, some insects contain bioavailable iron (Latunde-Dada, Yang, & Aviles, 2016). It is noteworthy that cooking methods may also influence the bioaccessibility of micronutrients. Recent research has found that beetles

Table 3
Fatty acid composition of the oil of some selected traditional edible insects in Western Kenya.

Fatty acid (%)	Agoro termite	Sisi termite	Riwo termite	Oyala termite	Black ant
Caprylic acid (C10:1)	N/A	N/A	0.4 ± 0.2	0.3 ± 0.0	N/A
Caprylic acid (C10:0)	N/A	N/A	0.2 ± 0.1	0.3 ± 0.0	N/A
Lauric acid (C12:0)	N/A	N/A	0.1 ± 0.1	0.2 ± 0.0	2.2 ± 1.0
Myristic acid (C14:0)	N/A	N/A	1.1 ± 0.2	0.7 ± 0.0	1.8 ± 0.0
Palmitic acid (C16:0)	26.1 ± 3.5	26.0 ± 2.3	38.3 ± 3.3	28.0 ± 0.1	28.7 ± 3.2
Palmitoleic (C16:1)	3.9 ± 0.4	5.8 ± 0.3	0.6 ± 0.0	3.6 ± 0.0	2.9 ± 1.1
Stearic acid (C18:0)	3.9 ± 0.4	3.8 ± 0.3	0.6 ± 0.0	3.6 ± 0.0	2.9 ± 1.1
Oleic acid (C18:1)	46.0 ± 3.5	50.2 ± 1.6	41.7 ± 2.6	49.2 ± 0.0	46.7 ± 1.3
Linoleic acid (C18:2)	10.1 ± 0.6	11.5 ± 0.4	5.0 ± 0.1	10.4 ± 0.1	10.2 ± 1.7
Linolenic acid (C18:3)	1.3 ± 0.1	0.2 ± 0.0	0.8 ± 0.0	0.7 ± 0.1	ND
Arachidonic acid (C20:2)	N/A	N/A	N/A	N/A	1.3 ± 0.0
Total saturated	39.2 ± 0.8	32.1 ± 0.5	49.4 ± 0.2	35.8 ± 0.0	38.7 ± 2.1
Total unsaturated	67.0 ± 0.9	67.8 ± 0.5	50.5 ± 0.2	64.5 ± 0.0	61.2 ± 3.5
Monounsaturated	9.9 ± 0.2	56.1 ± 0.6	44.6 ± 0.2	53.2 ± 0.0	49.7 ± 1.2
Polyunsaturated	0.4 ± 0.2	0.3 ± 0.0	0.1 ± 0.1	0.3 ± 0.0	0.3 ± 0.0

Source: Kinyuru et al. (2012).

N/A: Not available.

Table 4

Mineral (mg/100 g) content in some edible insects and some reference products on a total dry weight basis.

Insect species	From (country)	Ca	P	Fe	Mg	Zn
<i>M. nigeriensis</i>	Nigeria	1.0	14.9	9.6	61	N/A
<i>M. bellicosus</i>	Nigeria	21	136	27	0.15	N/A
<i>M. natalensis</i>	Nigeria	18	114	29	0.26	N/A
<i>Brachytrypes spp</i>	Nigeria	9.2	127	0.68	0.13	N/A
<i>C. aeruginosus</i>	Nigeria	4.4	100	0.35	0.09	N/A
<i>Z. variegates</i>	Nigeria	42	131	1.96	8.2	N/A
<i>A. trifascrata</i>	Nigeria	61	136	18	6.1	N/A
<i>A. infrecta</i>	Nigeria	8.6	111	1.78	1.01	N/A
<i>A. reticulata</i>	Nigeria	11	102	2.24	2.6	N/A
<i>A. litorata</i>	Nigeria	12	9.0	10	0.50	N/A
<i>A. verata</i>	Nigeria	8.6	110	2.0	1.56	N/A
<i>C. forda</i>	Nigeria	8.2	111	1.79	1.87	N/A
<i>A. mellifera</i>	Nigeria	15	126	25	5.2	N/A
<i>O. boas</i>	Nigeria	46	130	2.3	62	N/A
<i>O. monoceros</i>	Nigeria	N/A	N/A	85	18	N/A
<i>G. lucens</i>	Nigeria	N/A	N/A	N/A	N/A	N/A
<i>R. phoenicis</i>	Nigeria	54	685	31	132	N/A
<i>A. rufipes</i>	Nigeria	41	131	31	12	N/A
Agoro termite	Kenya	59	N/A	53	N/A	8
Sisi termite	Kenya	48	N/A	60	N/A	13
Riwo termite	Kenya	64	N/A	116	N/A	13
Oyala termite	Kenya	43	N/A	65	N/A	7.1
Black ant	Kenya	22	N/A	11	N/A	5.6
Meat/egg/chicken						
Meat ball (beef)	–	43	460	5.3	60	11
Egg	–	239	962	9.7	59	6.6
Chicken	–	37	466	2.3	60	3.9

Source: Banjo et al. (2006), Ifie and Emeruwa (2011), Igwe, Ujowundu, Nwaogu, and Okwu (2011), Paiko, Dauda, Salau, and Jacob (2012), Solomon and Prisca (2012), Kinyuru et al. (2012), Kinyuru et al. (2013), www.voedingscentrum.nl.

N/A: Not available.

(*Eulepida mashona*) had higher iron bioaccessibility (30.7%), compared to crickets (*Henicus whellani*) (8.11%), and boiling, reduced the bioaccessibility of both iron and zinc by about 50% in both species, while roasting did not (Manditsera et al., 2019b). Different handling, preparation and processing methods applied to edible insects, such as blanching, frying and drying, have also been found to affect the nutritive composition of edible insects and their products (Kauppi et al., 2019). Moreover, the nutritional composition of edible insects has been reported to vary depending on the insect's metamorphosis stage. The insect may be consumed as an egg, larvae, pupa or adult insect. Emerging products from edible insects currently consumed in Europe and North America, however, include whole dehydrated insects, which may be eaten as snacks or utilized as an ingredient in culinary food preparations, insect paste and flour that are useful in the production of cookies, snacks, candies, protein bars, hamburgers, sausages, to mention just a few (Kauppi et al., 2019; Nowak, Persijn, Rittenschober, & Charrondiere, 2016; Stoops et al., 2017; Sun-Waterhouse et al., 2016).

Apart from containing large amounts of minerals, insects can be an excellent source of vitamins. Eggs of honey bees contain 12.44 mg vitamin A, B2 and C per 100 g dry weight, their larvae contain 3.24 mg. Honey bee pupae contain 10.25 mg per 100 g dry weight (Bukkens, 1997). More examples are provided in Table 5.

2.5. Antinutrients

Some insect species also contain antinutrients in addition to basic nutrients. Some antinutrients are toxins, while others, like phytates and tannins, may also have beneficial effects, which are determined by both their chemical structure and employed dose (Muller-Harvey & McAllan, 1992). Phenol has been reported to exhibit some subtle effects on biota, including reduced fertility, diminished survival of young and inhibited growth (Babich & Davis, 1981). Antinutrients, such as hydrocyanide,

Table 5

Vitamin content (range) of some edible insect classes in Nigeria (mg/100 g) on a dry weight basis.

Order	Vitamin A	Mean	Vitamin B2	Vitamin C
Isoptera	0.026–0.05	0.14	1.54–1.98	3.01–17.76
Coleoptera	0.086–0.125	0.11	0.08–2.62	4.25–7.59
Orthoptera	1.0–0.068	0.03	0.03–0.08	0.0–8.64
Lepidoptera	0.028–0.034	0.03	0.09–2.21	1.95–4.52
Hymenoptera	NA	NA	0.12	NA

Source: Banjo et al. (2006), Ekop et al. (2010), Ifie and Emeruwa (2011), Igwe et al. (2011).

NA: Not available.

phytates, oxalates and tannins, have been found in some edible insects in Nigeria according to the literature (Ekop, Udoh, & Akpan, 2010; Ifie & Emeruwa, 2011). Four edible insects (grasshopper, palm weevil cricket and yam beetle) have been employed as a case study on this subject. The documented literature indicates the presence of hydrocyanide (2.187–3.203 mg/kg), oxalate (13.20–28.40 mg/kg), phytate (0.28–0.289 mg/kg) and tannin (0.329–0.430 mg/kg) respectively in four edible insects: i.e., *Glucens* (cricket), *H. meles* (yam beetle), *R. phoenicis* (Palm weevil) and *Z. variegatus* (grasshopper) (Ekop et al., 2010). Oxalate (total and soluble) contents of 29.00 and 19.32 mg/100 g and 21.72 and 14.01 mg/100 g have been respectively recorded for yam beetles and palm weevils. However according to Adesina (2012) and other previous studies (Vijayakumari, Siddhuraju, & Janardhanan, 1997), these values fall within safe and nutritionally acceptable limits.

Phytic acid, hydrogen cyanide (HCN) and tannin levels have also been reported as being low, and were 0.311, 2.651 and 0.42 mg/100 g and 0.276, 2.531 and 0.481 mg/100 g for yam beetles and palm weevils, respectively. Omotoso (2015) has made a similar observation of low and safe limit levels of those antinutrients for human consumption, as reported for winged termites, *Marcrotermes nigeriensis* Sjostedf and coconut beetles *Oryctes rhinoceros* L. (Termitidae: Isoptera).

Antioxidant properties have been reported for some insects, such as beetle *Cybister tripuncratus*, but have lower contents than the antioxidant activity displayed by the plant extract of *Calotropis procera* (i.e., 121.25 microgram per ml). Antinutritional properties have been indicated in this edible insect as being below 0.52%, a non toxic level with strong antioxidant properties (Shantibala, Lokeshwari, & Debaraj, 2014). Similarly, some edible insects like grasshoppers, crickets, African caterpillars and silkworms have been recently reported to have higher antioxidant compounds than in orange juice (Di Mattia, Battista, Sacchetti, & Serafini, 2019). Edible insects may, therefore, be considered quality food that enhances and maintain human health, and can protect aging caused by related diseases (Cito et al., 2017; Nkegbe et al., 2018; Stull et al., 2018), especially with adequate controlled processing methods and packaging to help retain the product's integrity and inherent antioxidant properties in raw edible insects.

2.6. Products

A documented report by Kinyuru, Kenji, and Njoroge (2009) from Kenya has shown that wheat buns enriched with 5% termite flour (*Macrotermes subhyalinus* Rambur (Isoptera: Termitidae) were more advantageous than standard bread loaves, thanks to some attributes like aroma, size, color, texture and consumer preference. This author indicated higher contents of niacin (0.90 versus 1.11 mg), riboflavin (0.17 versus 0.26 mg), calcium (10 versus 10.83 mg), folic acid (0.30 versus 0.33 mg), zinc (2.78 versus 3.23 mg) and iron (1.20 versus 1.80 mg) than those obtained with ordinary bread. This study by Kinyuru et al. (2009) has demonstrated the innumerable potential applications of edible insects in several other food formulations and utilization, including complimentary food. This concept can be employed with for different

Table 6

Formulations for complementary foods CF1, CF2 and CF3 (%).

Product	Amaranth grain (%)	Corn (%)	Dagaa fish (%)	Termite (%)	Soya bean oil (%)	Sugar (%)
CF1	73.0	15.0	3.0	8.0	0.6	0.4
CF2	71.0	15.0	3.0	10.0	0.6	0.4
CF3	66.0	15.0	3.0	15.0	0.6	0.4

CF1 contained $17.8 \pm 1.2/100$ g crude protein.CF2 contained $17.5 \pm 1.4/100$ g crude protein.CF3 contained $18.9 \pm 0.8/100$ g crude protein.

Source: Kinyuru et al. (2012).

food products, such as snacks, breakfast meals and confectioneries consumed in different countries by including the edible insects available in various countries for product formulations and consumers. Consequently, an urgent need arises for legislation to include them in food formulations worldwide so that the movement, sale and consumption of food products containing edible insects can be free from one country to another. Furthermore, based on the work reported by Kinyuru et al. (2009), there is also an urgent need to design and produce appropriate processing equipment that are scalable to be used on small and medium scales, and possibly on a large scale by farmers and processors. It is also important to ensure that equipment is gender-friendly and is adapted to rural communities for the sustainable production and processing of edible insects. The storage and packaging of different raw edible insects in various processed forms are also potential areas to which attention must be quickly made in order to promote the consumption of edible insects globally.

It is noteworthy, however, that some complementary foods have been formulated with termites as one of the fortificants used for Kenyan infants (see Table 6) (Kinyuru et al., 2012). Complementary food developed by including edible insects as ingredients for formulation was well liked by both infants and mothers (see Table 6) (Kinyuru et al., 2012). Research in Kenya has recently shown that adding 10% powdered cricket to cookies improved the dietary value compared to adding dairy powder, and that these cookies would be suitable for enhancing school feeding programs (Homann, Ayieko, Konyole, & Roos, 2017).

The readiness of European consumers to adopt edible insects as food was recently investigated. The authors suggested that entomophagy will be better promoted in Europe when they are introduced as part of their daily diet (Mancini, Moruzzo, Riccioli, & Paci, 2019).

In order to encourage entomophagy in Western diets, sensory appeal will be key to insects being valued as a pleasurable component of meals (Elhassan, Wendin, Olsson, & Langton, 2019). When edible insects are dried and milled into flour, they may prove more appealing in bread, frankfurters, and burgers. The willingness to pay for mealworm-minced meat for young children and pre-teens in schools has been recently assessed (Collins, Vaskou, & Kountouris, 2019). The authors emphasized the need for multiple marketing strategies that include early exposure, education, reducing the visibility of insect parts and celebrity endorsements as being vital to improve entomophagy in the Western world.

3. Ecological importance

Insects are indispensable for life on earth. They produce dyes, silk and wax, and pollinate plants. They are also the 'cleaners' of Mother Nature as they close the natural life cycle. The benefits of changing to insect-based foods are found in the nutritional value of insects, and also in positive ecological, economic and environmental impacts. In comparison to traditional livestock farming approaches, farming insects offers many other advantages, such as more feed-conversion efficiency, fewer GHG emissions, fewer land use areas with little environmental contamination and less water pollution, as reported by Glover and Sexton (2015) and Sun-Waterhouse et al. (2016). Fig. 3 (Gahukar, 2016) illustrates how insect farming is advantageous over other

livestock types as regards resource use and environmental impacts. The fact that insects have a widespread distribution, short reproduction cycles and high reproductive rates indicates other major advantages that underpin their economic potentials and impact (Schabel, 2010).

The discovery of new sustainable approaches to grow foods and to effectively employ biomass resources is a global priority, especially when the human population is estimated to reach 9 billion by the year 2050 (Béné et al., 2015). To this end, more sustainable farming practices must be developed for food production, storage, processing, packaging and unit production, as must suitable equipment to process edible insects, along with the conservation of oceans, and energy and water resources. Animal production has to increase to meet the increasing demand for meat products. Census data reveal that meat consumption worldwide (per year/person) during the 1997–99 period through to 2030 could go from 9.4 kg to 13.4 kg in sub-Saharan Africa (not including South Africa), from 25.5 kg to 36.7 kg in developing countries and from 88.2 kg to 100.1 kg in developed countries (FAO, 2014).

Hence, this indicates that today's meat consumption can be cut by substituting meat for edible insects (Schösler, De Boer, & Boersema, 2012). In line with the current United Nations Sustainable Development Goal 2 for year 2030, which features hunger eradication and malnutrition in all age groups among the 17 major highlighted goals that must be met (Von Grebmer et al., 2016), one pressing need is to feed an ever-increasing human population, especially the malnourished and underfed.

Therefore, the development of a sustainable, healthy and ethical global food supply is a high priority (Rubio, Fish, Trimmer, & Kaplan, 2019). Growing interest in bio-manufacturing and soft robotics makes insect cells promising candidates for efficient scalable food production. A new innovative approach for the future that utilizes engineered insect tissue as a food source with particular emphasis placed on the common fruit fly *Drosophila melanogaster* and the tobacco hornworm *Manduca sexta* as the most studied insects in muscle formation and myogenesis research has been recently reviewed (Rubio et al., 2019).

3.1. Pests as a delicacy

The impact that commercial development has on preferences for edible insects and the sale price of insect-based products (Césard, Komatsu, & Iwata, 2015) are crucial for both sustainable production and eating edible insects, especially in communities where edible insect farming is a major source of income. In Nigeria for instance, the sale price of some edible insects is not cost-effective and with ridiculously low consumption levels (Meludu and Onoja, 2018). Some insects, like beetle larvae, bees, termites, flies and ants, all play positive roles in the human food supply chain, plant reproduction and waste biodegradation. Others are considered pests and can substantially harm plants (e.g. preventing rice grain formation), humans and animals (e.g. transmitting diseases), particularly if these insects grossly outnumber that of their natural predators, or if they prey on other beneficial species.

Consequently, eating pest insects can be advocated from environmental and nutritional perspectives, and from the job creation opportunities and poverty alleviation viewpoints, for both male and female

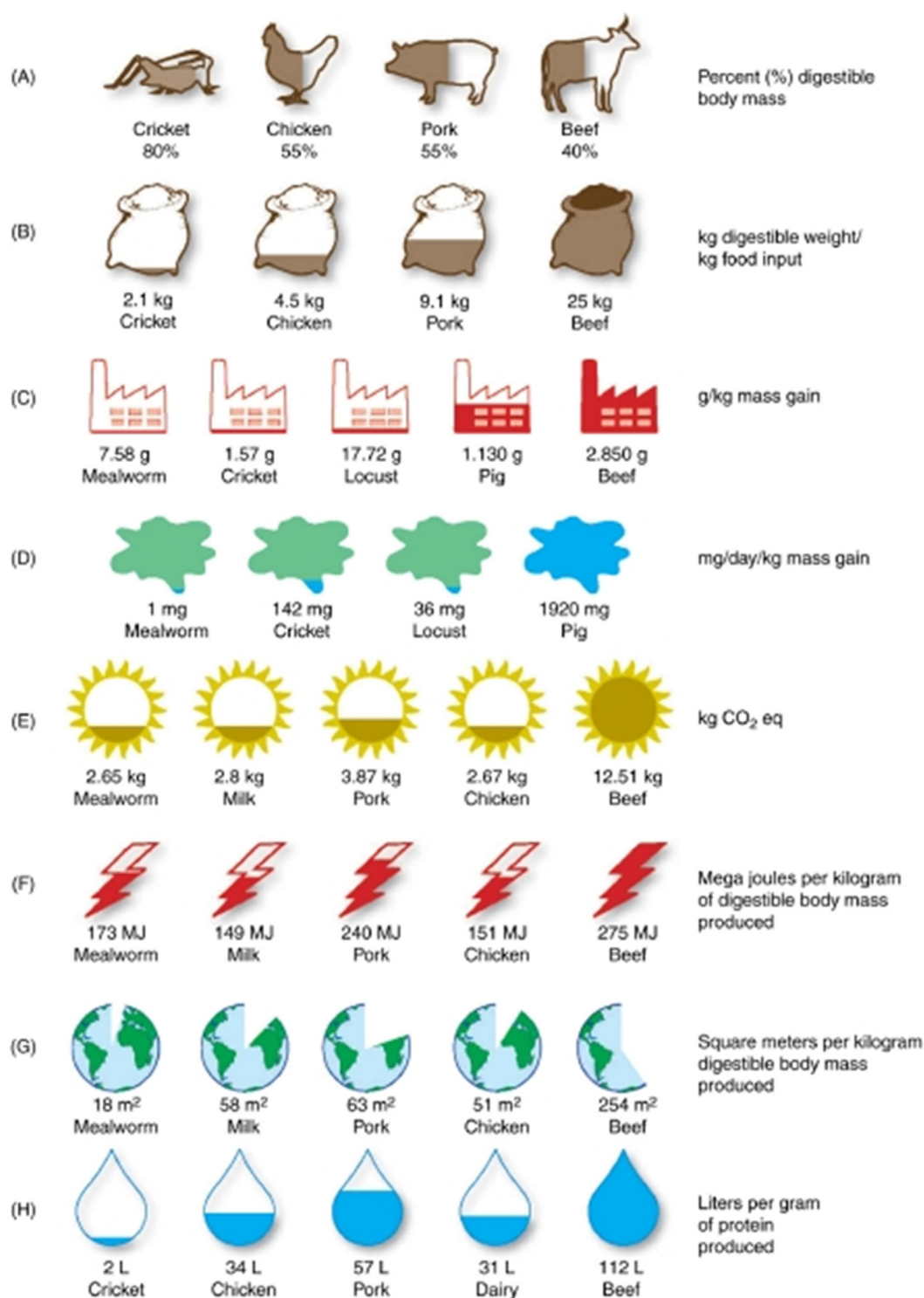


Fig. 3. Gahukar (2016) resource use and environmental impact parameters of insect farming versus other livestock.

(A) Percentage of digestible biomass (Van Huis, 2013); (B) feed conversion ratio (Van Huis, 2013); (C) production of greenhouse gas equivalents per kg of body mass gain (Oonincx et al., 2010); (D) production of ammonia pollution per kg of body mass gain (Oonincx et al., 2010); (E) global warming potential (Oonincx & de Boer, 2012; the GWP of 1 kg of fresh mealworms is 2.7 kg of CO₂-eq); (F) energy use (Van Huis, 2013); (G) land use (Oonincx & de Boer, 2012); (H) water use (Earth-policy.org, 2014; Pimentel & Pimentel, 2003; A Strategic Look at Protein, 2014; Ansc.purdue.edu, 2014; Waterfootprint.org, 2014; News.cornell.edu, 2014; Van Huis, 2013).

farmers. This approach could help to ease pest control pressure and pesticide use, while increasing the human intake of high-quality protein, plus the desired minerals and lipids, as evidenced by *Cirina forda* (Westwood), an insect pest of *Butyrospermum paradoxum*, the sheabutter tree (Akinawo & Ketiku, 2000). It could also provide insect farmers

with a source of income because they could process insects into different edible food forms and still use shea butter as a skin ointment.

Agriculture is the single most powerful, expanding and persistent human activity to bring about ecodegradation and to almost exhaust the Earth's ecosystem, as reported by Abbasi and Abbasi (2000) and

Premalatha, Abbasi, Abbasi, and Abbasi (2011).

Several studies have also proven that agriculture, and even farms, can negatively impact the environment (Killbrew & Wolff, 2010; Rodríguez, Sultan, & Hilliker, 2004; van der Werf & Petit, 2002). The damage that agriculture has caused to biodiversity has led to the “insect pests” phenomena by constantly producing situations that favor a few insect species which vastly multiply at the expense of several others that are eliminated. Enormous funds need to be spent to control these ‘pests’ by means of pesticides, which severely harm the environment (Premalatha et al., 2011). Such anthropogenic excess can be beneficial spin-off as lots of “insect pests” are edible and utilized as food in some countries (Cerritos, 2009; Ramos-Elorduy, 1997; Ramos-Elorduy & Pino, 1993). In Mexico, the crop pest *Sphenarium purpurascens* is controlled, captured and eaten as food. This practice allows hundreds of families to make a living. The annual profit made from harvesting this insect is almost \$3000 dollars per family, with close to 100 tons of extracted biomass (Cerritos & Cano-Santana, 2008). This potential advantage is wasted in most other countries which attempt pest destruction (Ramos-Elorduy & Pino, 1994).

Premalatha et al. (2011) have discovered that billions of dollars are spent every year to save crops worldwide that contain no more than 14% of plant protein by killing another food source (insects) that may contain up to 75% of high-quality animal protein. It is worth noting that collecting and farming insects offers employment and cash income to households or for larger industrial-scale operations. In developing countries in Southeast Asia, and in Southern and Central Africa, demand for edible insects exists. There it is quite easy to place insects on the market, and to collect and rear insects to be processed as street foods or sold as chicken and fish feed, because this practice lies easily within small-scale entrepreneurs’ reach, especially women. Another advantage of harvesting ‘pests’ like grasshoppers is that applications of chemical pesticides will drastically reduce, or might not even be needed, in field operations, and polluted water and soil levels will drop (Cerritos & Cano-Santana, 2008). The natural ecological balance is maintained because natural enemies survive on native insect populations in agroecosystems. Some examples of such are the red grasshopper and the bombay locust. The egg density of the red grasshopper pest *S. purpurascens* in Mexico is lower in fields, where more mechanical insect picking is practiced than in fields to which insecticides are applied (Ramos-Elorduy, 2009). In Thailand, pest infestation levels have substantially lowered thanks to hand collecting Bombay locusts (*P. succinta*) from corn fields (Boongrid, 2010).

Taking forest insects as food and not as pests will help to manipulate harvest practices or forest vegetation that will, in turn, increase, maximize or sustain insect populations. Cultivating insects under semi-farming conditions requires forests to be preserved rather than felled.

3.2. Feed conversion factor

When looking at insects as a product instead of a pest or sidestream, as exemplified above, other factors start to come into play. Rearing efficiency determines sustainability. For example, insects very efficiently convert organic matter into plant protein and dietary energy (with much higher yields than other animals, e.g. particularly mammals) (Deroy, Reade, & Spence, 2015; Nakagaki & Defoliart, 1991). This has to do with their poikilothermic nature, which makes metabolic warming unnecessary, as it is for endothermic animals. Thus, insects need to consume fewer calories from feed. The disadvantage of this attribute is that they only thrive at places with optimal temperatures. Here the consequence is that rearing insects for food in Western countries often entails making considerable investment in heating, and heating burdens the environment. Even so, the total life cycle analysis of some insects is positive compared to that of other farm animals even in Western countries (Ooninx & de Boer, 2012). Other advantages of employing insects as mini-livestock are they are extremely prolific, have rapid growth rates and extremely short life cycles. Capinera

(2004) reported a case study in which house crickets were extensively used as human food and how they acted as prolific breeders, while four breeding animals are required for each marketed animal.

The result of the poikilothermic nature combined with insects’ short life cycle is a high feed-to-food conversion ratio (Ooninx, Van Broekhoven, Van Huis, & van Loon, 2015). Schabel (2010) reported that the conversion of plant biomass into animal biomass by, for example caterpillars, was 10-fold higher than that of cattle, required much less land and led to a smaller environmental footprint. In order to accomplish the same protein yield, crickets need one twelfth and a quarter of the feed that is used for cattle and sheep, respectively, or roughly half the feed of pigs or chickens (Deroy et al., 2015). The feed conversion rate calculated for mealworm (*Tenebrio molitor*) was 2.2 kg/kg of live weight (Collavo et al., 2005; Ooninx & de Boer, 2012), while values ranged from 2.5 kg/kg to 10 kg/kg for chicken and beef for farm animals, respectively (Van Huis, 2013).

The efficiency of insects to convert feed into edible food is due partly to the higher fraction of consumed and digested insects (up to 100%) versus conventional meat (e.g. 55% for chicken and pigs, while only 40% of cattle’s live animal weight can be consumed and digested), and insects more efficiently recover crude protein (Collavo et al., 2005).

The quantity of animal feed needed for meat production is vast. This implies the potential to drastically reduce the water employed for irrigating land to generate feed crops for the livestock and pesticides used in animal husbandry (Vogel, 2010) through more effective rearing of edible insects, especially if the right insect breeds are employed.

3.3. Waste streams as feed

There are economic advantages when insects are considered as a protein source as they can be raised cheaply on agricultural biowaste, abattoir blood, food waste and human waste (Katayama et al., 2008). Henceforth, organic side streams and unused biowaste can be transformed into high-value quality protein as animal feed or human food (Veldkamp et al., 2012). Ultimately, in order to guarantee that basic hygienic conditions and consumer safety are met, transformation conditions would have to be properly legislated. Beetles, grasshoppers, flies and crickets consume agricultural waste or plants like silage and grass that humans do not eat (Dossey, Morales-Ramos, & Rojas, 2016). When beetles feed on fallen trees in forests, they help with the decomposition process and the forest’s balance is restored (Gray, 2014). The conversion of the biomass not consumed by humans into edible animal biomass by insects offers a competitive advantage to insects as they do not need to compete with the human food supply or the feed needed for chickens and pigs, which feed mainly on grain (Vogel, 2010). Commercial diets can be utilized to rear industrial mass insect production (Dossey et al., 2016). For example, in Thailand a diet containing protein, sugar or kitchen waste has been used to rear weaver ants *Oncophylla smaragdina* Fb. (Offenberg, 2011).

Thus, waste streams provide excellent insect feed opportunities, although efficient insect rearing strongly depends on feed quality. So rearing efficiency will be compromised if feed composition is sub-optimal.

3.4. Land and water uses

The production of insects does not require a large area of land and water usage is minimal (FAO, 2013). It has been estimated that the land area required to yield the same quantity of protein is about 1 hectare for mealworms, 2–3.5 hectares for pigs or chicken, and 10 hectares for cattle (Ooninx & de Boer, 2012). Stehfest and co-workers investigated the benefits of changing diets to the climate. They reported that the replacement of meat with insects as a major protein source could lead to 2700 mega hectares of pasture and 100 mega hectares of cropland being abandoned which, in turn, would result in vast carbon uptake from vegetation regrowth. Additionally, nitrous oxide and methane

emissions would substantially drop (Stehfest et al., 2009).

3.5. Greenhouse gas emissions

Overall, average temperatures have risen by 0.8°C in the 20th century and are predicted to keep rising, whose consequences are expected to be negative and significant. According to the recent Intergovernmental Panel on Climate Change (IPCC) report, meeting a target of 1.5°C above pre-industrial temperatures will require urgently cutting carbon pollution, as well as a widespread dietary shift to eating less meat (IPCC, 2018).

Global warming is caused primarily by GHG emissions from human activity (Smith, Schellnhuber, & Mirza, 2001). The livestock sector accounts for approximately 8–18% of anthropogenic GHG emissions (Herrero et al., 2015).

In emission terms, producing 1 kg of beef cattle involves the equivalent emissions of 14.8 kg of CO₂ (Fiala, 2008), with 1.1 kg and 3.8 kg respectively for chickens and pigs (Steinfeld et al., 2006). Mealworm larvae, locusts and crickets emit 100-fold fewer GHG emissions and 10-fold less ammonia than beef cattle and pigs (Ooninx et al., 2010). Scarab beetles, cockroaches and termites are the only insect species to emit methane (Hackstein & Stumm, 1994). Methane production is the result of bacterial fermentation by Methanobacteriaceae in the hindgut of insects (Egert, Wagner, Lemke, Brune, & Friedrich, 2003). If insects were raised and consumed by humans instead of cows, today's GHG emissions would certainly be lower, by as much as 10% (Ooninx et al., 2010). The amounts of emitted GHG (ammonia, nitrous oxide, methane and carbon dioxide) can be found in Fig. 3c. The emission rates of these gases have been reported by many researchers to be closely related to the varying conditions used to farm animals or insects (Cabaraux et al., 2009; Harper et al., 2009; Lundy & Parrella, 2015; Ooninx et al., 2010).

Research at the University of Wageningen in The Netherlands reports the production of CO₂ per kilogram of mass gain for five edible insect species (i.e. mealworms *Tenebrio molitor*, crickets *Acheta domestica*, locusts *Locusta migratoria*, beetles *Pachnoda marginata*, and wood roach *Blaptica dubia*) was 39–129% compared to pigs and 12–54% compared to cattle (Ooninx et al., 2010). About 2.7 kg CO₂ is produced per 1 kg of poultry (Ooninx & de Boer, 2012). The environmental impact caused by insect rearing will also depend on insect species and if they are utilized as food or feed (Ooninx et al., 2010). Ooninx and de Boer (2012) reported that farm animals are less sustainable than mealworms (*Tenebrio molitor*), particularly in terms of their global warming and land use potentials.

Beef cattle produces 100 times more methane, while pigs generate 50-fold more CO₂, 8-fold more ammonia and 20-fold more nitrous oxide than house crickets. Greenhouse gases (CH₄, CO₂ eq., N₂O and NH₃) production (the average of six standard deviations) per kilogram of body mass per day for five insect species, pigs and beef cattle have been investigated (Ooninx et al., 2010). In yellow mealworms (*T. molitor*), direct GHG emissions came to only 0.29%, while the production of a mixed grain and carrot diet accounted for 56% of the total quantity (Ooninx & de Boer, 2012). This confirms a minimal environmental impact when mealworms are utilized as a source of protein. Insects can meet the need for alternative protein sources, especially when considering the problems associated with food production in the animal sector and GHG emissions. Based on the results of a life cycle analysis that examined the entire production process, the global contribution of the food-producing animal sector is 9% for CO₂, 35–40% for CH₄ and 65% for N₂O, whereas the most polluting component, nitrogen dioxide (NO₂), was emitted from farm manure and urine (Gahukar, 2016; Steinfeld et al., 2006).

3.6. Energy use

Nowadays the energy spent on growing feed crops for the livestock

sector is also responsible for pollution (Ooninx et al., 2010). Energy demand by insects varies depending on location. For instance, pumping water for irrigation purposes in agriculture is what most contributes (2.52–15.72 t/ha) to CO₂ emissions in India (Reddy et al., 2015). As insects are poikilothermic (i.e., their body temperature depends on the ambient temperature), they need higher temperatures to thrive, which results in bigger energy demands in areas with a moderate or cold climate.

4. Food safety aspects

Rearing insects for food poses questions about the safety of eating insects. Although insects are collected from the wild as part of many cultures from Africa, Asia and Latin America, rearing them for the specific goal of consumption means that it is important to ensure a product's safety (Murefu, Macheka, Musundire, & Manditsera, 2019). Even though insects pose fewer risks of transmitting zoonotic infections like H1N1 (bird flu) and BSE (mad cow disease) to humans compared to mammals and birds, other safety-related factors are still important and should be made priority research areas when contemplating the intensive rearing of insects (FAO, 2013). We divide them into three main topics: microbial contamination, toxicological hazards and allergenic reactions.

4.1. Microbiological contamination

A complex microbial community (bacteria, viruses, fungi, protozoa and archaea), which spans the symbiotic spectrum from mutualistic to pathogenic, can be associated with insects, like any other living organisms (Douglas, 2015; Engel & Moran, 2013). Such microbes are known as the microbiota of an organism, and can be associated with insects in both farming environments and nature. Most of the microbes present on or in insects are considered harmless to human consumers, and are not believed to cause food spoilage (Marshall, Dickson, & Nguyen, 2016). Many microbes related with industrialized insect farming for human consumption and insects as food ingredients are probably encountered in other food production/processing environments. Hence reviewing insects' internal microbiome aspects is important because they are unique when considered to be food, and when processed as mini-livestock, especially by industries that utilize whole insects, including their digestive system and its contents (Marshall et al., 2016).

The gut of *Acheta domestica* L. (house cricket) contains bacteria of genera *Yersinia*, *Bacteroides*, *Citrobacter*, *Klebsiella* and *Fusobacterium* (Ulrich, Buthala, & Klug, 1981). These microbes could play important active roles for crickets for the digestion of proteins, carbohydrates and lipids (Kaufman & Klug, 1991). The microbial community alters with changing diet (Santo Domingo, Kaufman, Klug, & Tiedje, 1998). Recently, a study demonstrated that the gut microbial community of field crickets caught in the wild was more diverse than laboratory-reared crickets, fed chemically defined diets (Ng, Stat, Bunce, & Simmons, 2018). The yellow mealworm, *Tenebrio molitor* L., hosts bacteria in genera *Actinobacillus*, *Propionibacterium*, *Citrobacter*, *Serratia*, *Bacillus*, *Dermabacter*, *Brachybacterium*, *Clavibacter* and *Exiguobacterium* (Liu, Ye, Zhang, & Zheng, 2011). *Enterobacter asburiae* Brenner et al., and an unclassified *Bacillus* species, have been found in the gut of the wax-moth *Galleria mellonella* L. (Yang, Yang, Wu, Zhao, & Jiang, 2014).

The mopane caterpillar, *Imbrasia belina* Westwood, is commonly eaten in South African countries. It contains several moulds, including *Cladosporium*, *Aspergillus*, *Penicillium*, *Phycomycetes* and *Fusarium* (Marshall et al., 2016). These authors also discovered potential human pathogenic bacteria *Bacillus cereus*, *Escherichia coli* and *Klebsiella pneumoniae* in some samples of processed caterpillars. As many of these fungi and bacteria are commonplace in production/processing environments, the discovery of these microbes in edible caterpillar products after boiling and drying might not indicate the microbial origin of

insect gut (Gashe, Mpuchane, Siame, Allotey, & Teferra, 1997).

It has been reported that each insect species appears to host a distinct group of bacteria, with a few common genera; e.g. *Bacteriodes*, *Enterobacter*, *Bacillus* and *Citrobacter* (Belluco et al., 2013). The first two genera have also been found in the human digestive tract. Members of the genus *Yersinia*, which was detected once in the gut of house crickets, can be pathogenic for humans (Ulrich et al., 1981). *Yersinia* also occurs in other insects like fleas and arthropods that act as a natural reservoir. The genus level classification does not suffice to connect these bacteria to those that could prove harmful to humans. Generally speaking, insects' naturally-occurring gut bacteria do not apparently overlap those found in farm environments or might be harmful to humans (Marshall et al., 2016).

Definite human food-borne pathogens, e.g. *Salmonella* spp. and *Listeria monocytogenes*, have not been isolated from guts of farm-raised yellow mealworm (*T. molitor*), superworm (*Zophobas morio* Fab.), butterworm (*Chilecomadia moorei* Silva Figueroa), house cricket (*A. domesticus*) and wax moth (*G. mellonella*) (Giaccone, 2005). *Citrobacter intermedium* Sledak, *E. coli*, *Micrococcus* spp., *Bacillus subtilis* Ehrenberg and *Streptococcus* spp. have all been isolated from lesser meal worms (*Alphitobius diaperinus* Panzer) collected in poultry houses (Harein, Casas, Pomeroy, & York, 1970). Simple food processing interventions, like boiling insects in water for a few minutes, removes live bacterial cells. However, spores have survived this process and could later germinate, and this could cause human illness or food spoilage (Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012).

It is noteworthy that the populations and microbial prevalence related to wild insects, and those with cultivated insects, might differ (Marshall et al., 2016). These differences are largely accounted for by the kind of food that insects eat and their production environment. Hence proper farming techniques should be adapted to control pathogens because they may prove harmful for humans (Marshall et al., 2016). An example of this is the study carried out by Garofalo et al. (2017), who detected the presence of *Listeria* spp., *Staphylococcus* spp., *Clostridium* spp. and *Bacillus* spp. in processed marketed edible insects.

The gut content to total mass ratio is particularly interesting for preparing insects as food because it is virtually impossible to leave a gut devoid of its microbiota in most insect species (Engel & Moran, 2013). The intestinal tract volume varies from 0.05 to 2 mL depending on the species (Schlüter et al., 2017). Average bacterial densities of 10^6 – 10^{12} bacteria per milliliter of gut content were detected in *Periplaneta americana* (Cazemier, Hackstein, Den Camp, Rosenberg, & van der Drift, 1997). The microbial biomass accounts for 1–10% of the total insect body and depends on insect species (Douglas, 2015). Different feed substrates can alter species' gut microbiota spectrum and the proportion of individual bacteria, depending on insect species and their developmental stage (Jung et al., 2014; Liang, Fu, Tong, & Liu, 2014; Pérez-Cobas et al., 2015; Yun et al., 2014) which, in turn, might raise the microbial count of human-pathogenic microorganisms. Microbiota composition also alters while complex individual insect development takes place, which can be influenced by environmental conditions and diet (Singh et al., 2015; Vojvodic, Rehan, & Anderson, 2013). Various batches of fresh *T. molitor* larvae, their feeding substrate (wheatmeal) and frass have been recently evaluated by Osmani et al. (2018). While the microbial contamination of the wheat supplied to larvae was low, both larvae and frass contained large quantities of Enterobacteriaceae, lactic acid bacteria and some mesophilic aerobic species. Sporeforming bacteria were identified to a lesser extent. *Enterobacter* spp., *Erwinia* spp., *Enterococcus* spp., and *Lactococcus* spp. were found to be the dominant genera in both larvae and frass, whereas *Klebsiella* spp., *Pantoea* spp., and *Xenorhabdus* spp. were found as a minority. Shiga toxin-producing *Escherichia coli* was absent. Two microbiological contamination paths were hypothesized, which were transmitted via feed and through the vertical path. The EFSA proposed a possible classification of substrates for insect breeding with several potential hazard levels (EFSA, 2015). Special attention must be paid to human-

pathogenic microorganisms that cannot be avoided, not even under controlled breeding conditions, and adequate processes must inactivate them. Contamination by toxin-forming and human-pathogenic species of allochthonous microbiota (i.e. transient microbes in fecal streams) may probably be managed by controlled breeding conditions, even though a high density of insect monocultures can spell further difficulties (Eilenberg, Vlak, Nielsen-LeRoux, Cappellozza, & Jensen, 2015). When insects are processed to produce fractions or extract enzymes, we must assume that unavoidably high microbial contamination exists *ab initio*, which needs to be carefully managed by following suitable processing steps, such as heating processes (Schlüter et al., 2017).

Initial data are available on the effects that different processes have on the microbiological status of whole insects (FASFCFSIIHC, 2014; Schlüter et al., 2017). Many of the methods employed to extract protein and lipid fractions or enzymes from insects remove microbial contamination from raw materials. Determining critical control points while producing/processing insects will, however, be necessary (Stoops et al., 2016), including intermediate decontamination stages.

4.2. Toxicological hazards

A thorough discussion about insect contents in noxious substances, as with other vegetables and animals, should include natural toxicants, defined henceforth as compounds that are either naturally present in insect feed or synthesized by insects. As the natural toxicants' domain is a complex one, it is relevant to differentiate between unsafe and safe insects, rather like in the world of mushrooms (Holt, 1885). Some insects produce harmful substances against predators, or they warn their enemies by displaying color patterns (Zagrobelyny et al., 2009). Other attempts involve deceiving attack by mimicking colors of true toxins, which is otherwise known as Batesian mimicry (Bates, 1981).

There are basically two categories of poisonous insects: phanero-toxics and cryptotoxics. The former has organs that are used for the synthesis of poisons, e.g., as in ants and bees. Generally speaking, such substances are left inactivated in the digestive tract. Potential risks are posed during the oral and esophageal passage of bites and stings of ants and bees. If high levels of some biogenic amines are present, these stings and bites might be hazardous.

Cryptotoxics are when potentially noxious substances are present that result from their synthesis or accumulation. These substances can be localized in specific structures or diffused in different body areas. This kind of insect can be potentially dangerous for humans after being ingested.

In order to simplify the distinction between both categories and to avoid the risk of ingesting a toxicant, a long time ago Holt (1885) concluded that insects, which feed on edible plants, could be considered safe, while others need to be more carefully selected.

Some insect-linked chemical hazards, e.g. metabolic steroids (i.e. dihydrotestosterone, testosterone) have been encountered in beetles (Dytiscidae family) (Belluco et al., 2013). If such steroids are regularly eaten, they may cause hypofertility, growth retardation, masculinization in females, jaundice, edema, and even liver cancer (Belluco et al., 2013). The cyanogenic glucosides that may be present in many plants, and used to deter predators thanks to their hydrogen cyanide content and bitter taste, may also be present in some insects (Zagrobelyny et al., 2018). These cyanogenic substances might also be found in Coleoptera and Lepidoptera insects. They may inhibit enzymes, e.g. carbonic anhydrase and succinate dehydrogenase, as well as metabolic pathways, like oxidative phosphorylation, given their high affinity to ferrocytochrome oxidase (Blum, 1994).

Antinutrients like phytate, oxalate and tannin, (Ekop et al., 2010; Shantibala et al., 2014) and thiaminases (Nishimune, Watanabe, Okazaki, & Akai, 2000) might also play a part. It is important to determine if antinutrients and toxins are absorbed by insects from their feed, or if they are synthesized by insects. The breeding conditions for insects should also comply with applicable food safety regulations. This

means that the insects selected to produce food ingredients and food ought to be stored so as to prevent, or minimize, externally introduced drugs antinutrients or toxins from accumulating.

4.2.1. Synthesized by insects (Phanerotoxics)

There are insects that synthesize compounds that are toxic to humans. One example is monoterpene cantharidin (2,6-dimethyl-4,10-dioxatricyclo-[5.2.1.0^{2,6}] decane-3,5-dione), which is synthesized by the Spanish fly (*Lytta vesicatoria*) and several beetles. This monoterpene is bound to proteins which are, therefore, referred to as cantharidin-binding proteins. If consumed, toxic effects include nausea, difficulty swallowing and vomiting blood (Till & Majumdar, 1981), and can prove lethal if it penetrates the blood stream (Blum, 1994). The eggs and ovaries of *Lytta vesicatoria* (Coleoptera), which also harbor cantharidine, cause bladder and urethral irritation, and sometimes priapism.

Longhorn beetles (genera *Syllitus* and *Stenocentrus*) are the only sources of toluene known in Arthropoda (Blum, 1994), which is a nervous system depressant toxic for kidneys, the liver and the brain. Hence eating these insects is not recommended. Darkling beetles (Tenebrionidae) produce quinones and alkanes (Brown, Doyen, Moore, & Lawrence, 1992), while some moth species of the genus *Zygaena* possess cyanogenic glycosides (Zagrobelyny et al., 2009). The risk potential linked to such substances should be investigated, and the same applies to the toxins that originate from microorganisms in insect gut; e.g., the toxins of genera *Clostridium* *Bacillus* and *Aspergillus*.

No data are available about the presence of toxins in insect species considered to be potentially edible, nor about the toxigenic potential of insect components. A 90-day feeding trial demonstrated that *T. molitor* larvae did not lead to any adverse effects in the rats fed a dried powder. The highest dose used was 3000 mg/kg body weight/day (Han et al., 2016). In certain regions, traditional insect intake suggests that eating insects poses no health risk (Anankware, Fenig, Osekre, & Obeng-Ofori, 2015; De Foliart, 1999). Some specific cases might contain knowledge on traditional insect uses in certain countries that is comprehensive enough to be the basis for a “history of safe use.” Yet to date, this claim has not yet been scientifically or systematically investigated, particularly because of processing steps, where harmful components present only in trace amounts can be enriched together with actual target components during fractionation.

Antinutrients are another class of harmful substances that must be taken into account. They are particularly relevant for people on a poor diet with limited sources of nutrients, especially vitamins. Following *Anaphe venata* caterpillar consumption in Africa, one individual case has been described of insects’ antinutritional activity. This insect can cause thiamine deficiency and the consequent ataxic syndrome during the season when it is normally ingested. Analyses have shown that thiaminase levels are 3-fold higher than in common silkworms. As dietary intake is thus constrained, some Nigerian people have thiamine deficiency (Adamolekun, 1992). Nonetheless, adequate cooking methods can minimize thiaminase (Nishimune et al., 2000).

The toxic potential of antinutrient content and antinutrients should be minimized by choosing convenient processing and breeding conditions (Schlüter et al., 2017). Eating selected insect parts can prevent toxic effects, as shown in Friuli-Venezia Giulia, a region in east Italy. The mountain inhabitants from this region have a tradition of consuming Lepidoptera of the genus *Zygaena*, which are bright colored and potentially unsafe as they concentrate cyanogenetic glycosides. These chemicals may be detoxified partially by rhodanase activity in the presence of sulfur, which increases the risk for undernourished subjects on a low sulfur diet. However, consumers in these regions exclude most of the body and ingest sweet ingluvies, where toxicants do not accumulate (Zagrobelyny et al., 2009).

4.2.2. Absorbed from the environment (Cryptotoxic)

It is worth mentioning that the first chemical deliberation about insects as part of our diet is that all the pesticides adopted against them

are potentially dangerous for humans, principally if products are collected through wild harvesting instead of from controlled farming. This consideration is sustained by a case from Thailand where, after running a major disinfection program, dead insects were placed on the market, and caused health problems, and even death, for consumers due to pesticide poisoning in dead insects (De Foliart, 1999). A second case that contemplated this concern took place in 1988–1989 in Kuwait, where the locusts that invaded the country were sprayed with pesticides to save crops and vegetation. The results from the captured locusts showed that chlorinated pesticides were not present at high levels in waste, while a relatively large amount of organophosphorus pesticides was found, particularly sumithion and malathion, which are respectively taken to be moderately and slightly toxic. This posed a risk for the people who ingested locusts (Saeed, Dagga, & Saraf, 1993). When insects are considered pests, potentially edible insects may generally possess higher than acceptable levels of chemicals due to the constant usage of pesticides (Banjo et al., 2006). Obviously, it is not always feasible to collect insects for consuming purposes in nature, particularly in Europe (Mlcek, Rop, Borkovcova, & Bednarova, 2014).

However, harmful substances may also be present in insect feed. Generally, accumulation of toxins from feed is a simple survivor strategy in the evolutionary process but, favorably, some of these compounds can lose their properties through cooking processes (Berenbaum, 1993). Brown et al. (1992) showed the existence of benzoquinone in insects. This substance belongs to the quinones family, which are extensively distributed phenolic compounds in plants. Most quinones have a bitter taste (Schwartz, von Elbe, & Giusti, 2008). This substance is present in Tenebrionidae, insects used in alternative medicine, such as *Ulomoides dermesetoides*, which is reared in Argentina and used to treat arthritis, asthma, Parkinson’s disease, diabetes, cancer and HIV. The presence of benzoquinones has been manifested in 30-day-old adults (Crespo et al., 2011). With the presence of benzoquinone, Tenebrionidae may be cytotoxic against human lung carcinoma epithelial cell line A-549, which results in damaged DNA. Nonetheless, cytotoxicity suggests being targeted to not only cancer cells, but also to other targets. Some scientists state that the DNA damage mechanism could lead to cancer in people who come into contact with benzoquinones, precisely ethyl-benzoquinones and methyl-benzoquinones, which are also enclosed in adult flour beetles *Tribolium castaneum* and *Tribolium confusum* (Lis, Bakula, Baranowski, & Czarnewicz, 2011). However, the IARC (International Agency for Research on Cancer) officially declares that no epidemiological data are available on the carcinogenicity of 1,4-benzoquinone. There is insufficient evidence in experimental animals for the carcinogenicity of 1,4-benzoquinone. Hence classification exists for its carcinogenicity for humans (Group 3; IARC and WHO, 1999).

In Australia, accumulation of arsenic is identified in *Agrotis infusa* (Lepidoptera). This harmful element is consumed through diet, and emerges from both human pollution and natural sources. The insect is able to disperse arsenic over a wide radius given its migration habits (up to 100 km) (Green, Broome, Heinze, & Johnston, 2001).

Another compound category that may bioaccumulate in insect bodies is heavy metals. In a study into an outbreak, Handley et al. (2007) have shown high lead content in chapulines (dried grasshoppers) from Oaxaca (Mexico), and associated them with high blood lead levels in Californian pregnant women and children. Chapulines were not the only source of lead in the studied population. Certainly, metal levels in food depend on environmental contamination and food preparation, and dehydration increases toxic concentrations, which was the case of grasshoppers from Oaxaca. Along the whole soil-plant-insect-chicken food chain, potential heavy metal content and bioaccumulation have also been investigated. The results indicate that Cd continuously decreases with increased trophic levels, but Zn and Cu concentrations slightly rise from plant to insect larva. One important path to prevent bioaccumulation is through the disposal of feces. Metal concentrations in chicken muscle, blood and liver were most irregular,

but were higher in liver and lower in blood. Chickens fed insect larvae accumulated significantly high Pb levels in their livers, which suggests that heavy metals accumulation in distinct animal organs should not be overlooked (Zhuang, Huiling, & Wensheng, 2009). However, according to this evaluation, insect ingestion did not produce a risk factor. Crickets, like other soil-dwelling insects, are also able to introduce solid waste contaminants into the food web by preying on discarded consumer products (Gaylor, Harvey, & Hale, 2012). Chemical hazards in insects depend mainly on plant feed contamination, and may be controlled by selected farming and dietary conditions (Belluco et al., 2013). Recently, Poma et al. (2017) concluded that levels of hazardous chemicals in edible insects were lower than those in common animal products.

4.3. Allergenicity

FAO and WHO (2001) define food allergic reactions as “adverse reactions to an otherwise harmless food or food component that involves an abnormal response of the body’s immune system to specific protein(s) in foods”. Anaphylactic reactions and other isolated allergic episodes have been described in the medical literature as regards eating insects (Choi, Shin, Kim, Ye, & Park, 2010; Ji, Zhan, Chen, & Liu, 2008; Yew & Kok, 2012). The pan-allergen concept encompasses families of related proteins that are widely distributed in nature, and are implicated in general vital processes. So highly conserved sequence structures, functions and regions are shared by plant pan-allergens. They are responsible for frequent IgE cross-reactions, even between unrelated plant and pollen sources of food allergens. Although it is generally contemplated as minor allergens, sensitization to pan-allergens can be a problem because it incurs the risk of developing multiple sensitizations (Hauser, Roulias, Ferreira, & Egger, 2010). In arthropods, pan-allergenic structures have been identified, which include insects (e.g. beetles, bees, cockroaches, and locusts), arachnids (e.g. mites) and crustaceans (e.g. crabs, lobsters, and shrimps) (Ribeiro, Cunha, Sousa-Pinto, & Fonseca, 2018). Pan-allergenic structures have also been documented in molluscs (Kamath et al., 2013; Leung et al., 1996). Pan-allergenic tropomyosin can evoke allergic reactions to crustaceans, and also to insects and mites (e.g. cockroaches) (Hemmer, 2010; Reese, Ayuso, & Lehrer, 1999). Other pan-allergenic or ubiquitous structures may also develop a possible allergic cross-reaction to arthropods and, consequently, in edible insects in atopic subjects.

The primary sensitization to these pan-allergenic or ubiquitous structures, and to species-specific allergens, is possible. Unpredictable allergic cross-reactions may occur due to sensitization to pan-allergenic structures because allergic consumers cannot directly identify the allergen source. This complication can become more serious when potentially allergenic fractions, for example the protein fraction, are extracted to be utilized as an ingredient in food compounds. Bearing in mind the relatively high frequency of inhalation allergies to flour mites, cockroaches and house dust mites in the general population, *versus* classic food allergies (Calderón et al., 2015; Pomés and Arruda, 2014), a much bigger population segment may be influenced by possible cross-reactions between insect pan-allergens and mites.

Nevertheless, the major allergenic structures in insects are glycoproteins, which encompass allergens from insect venom (e.g. phospholipase A, hyaluronidase). In arthropods, today 239 individual allergens are registered in line with the Allergen Nomenclature Subcommittee requirements of the International Union of Immunological Societies and the WHO. They are chiefly pan-allergenic or ubiquitous proteins which, more clearly put, can be classified as muscle proteins; e.g., troponin C, actin, myosin, tropomyosin, circulating proteins (i.e. defensin, hemocyanin), cellular proteins (i.e. tubulin), enzymes (i.e. α -amylase, triosephosphate isomerase, arginine kinase, trypsin, phospholipase A and hyaluronidase). Approximately 50% of the arthropod database entries are related to insect allergens, but no systematic research in different insect development stages has yet been conducted.

Thus, the extent to which insect development stages contribute to allergenicity remains ambiguous (Schlüter et al., 2017).

Like glycoproteins, other immunomodulatory or allergenic substances are known in arthropods. For instance, immunogenic glycostructures have been documented, of which some have an anaphylactic potential. There is evidence that allergenic glycoepitope galactose- α -1,3-galactose (α -Gal) may trigger anaphylactic reactions (Commins & Platts-Mills, 2013; Platts-Mills, Schuyler, Tripathi, & Commins, 2015). The tick larva or tick bite of *Amblyomma americanum* (Arachnida, Arthropoda) may cause α -Gal sensitivity with anaphylactic cross-reactions to non primate meat, where α -Gal is a blood-group substance. There are no data available today on the presence of α -Gal allergens in edible insects.

The likely contamination of insects with pathogenic moulds with a known allergenic potential, e.g. *Aspergillus*, *Penicillium* or pathogenic yeast, e.g. *Candida* (Fukutomi & Taniguchi, 2015), should be considered a secondary trigger of allergic reactions; i.e. not due directly to insects. Therefore, measures need to be taken to ensure that cultivated insects are free of organisms with an allergenic potential.

Regarding the use of individual (micro)components from insects, research into their levels in insects, optimized extraction methods and safety risk assessments should be performed. For example, the carmine colorant has been characterized to trigger severe allergic reactions to food (Wüthrich, Kägi, & Stücker, 1997). Carminic acid alone, or bound to protein (Wüthrich et al., 1997), and co-extracted IgE-binding proteins from cochineals, have been indicated as probable triggers of the anaphylactic reactions described in relation to carmine (Chung, Baker, Baldwin, & Chou, 2001). The binding of IgE antibodies from individuals allergic to carmine to extracted cochineal proteins has been repressed *in vitro* by carmine extracts (Dubey, Moeller, Schlosser, Sorensen, & Holmskov, 2015). The results indicate allergenic proteins in cochineal and their presence in carmine. This means that we cannot rule out the possibility of carminic acid contributing to the described effects.

However, the positive health effects of chitin described in the chapter on nutritional value has also been characterized as another molecular structure with immunomodulatory potential. There are documents which advocate that chitin may enhance the formation of allergen-specific IgE antibodies, which play a key role in the pathomechanism of immediate hypersensitivity reactions. This has been reported in murine sensitization research with, for example, mice with chitin-binding allergen Blo t 12 from mites that are allergic to *Aspergillus fumigatus* (*Blomia tropicalis*) (Dubey et al., 2015; Zakzuk, Benedetti, Fernández-Caldas, & Caraballo, 2014). Chitin-binding vicilins (leguminous storage proteins) have been documented in *Erythrina velutina* and *Enterolobium contortisiliquum* (Macedo et al., 2008; Moura et al., 2007). In other edible legumes, e.g. soybeans and peanuts, vicilins have been described as being important allergens (Burks, Cockrell, Stanley, Helm, & Bannon, 1995; Holzhauser et al., 2009). It is not clear if chitin complexes and known allergenic vicilins from dietetically relevant legumes possess any immunomodulatory potential for enhancing the allergy-mediating antibodies formation in exactly the same way as that characterized for chitin-binding Blo t 12 from mites.

Different exposure types, i.e. injection, inhalation, skin contact and ingestion, have been documented for allergies and/or cross-allergies to insects. Potential exposure to insect venom, known to cause allergic reactions and even anaphylactic shock after injections, occurs in connection with processing whole insects if venom is not inactivated by processing. To date, however, allergic reactions, including anaphylactic reactions after eating insects, have been sporadically documented.

There is still considerable ambivalence as to the extent to which primary sensitization to insects occurs, and to what extent it may lead to allergic reactions. It is also necessary to define possible cross-sensitivities to arthropod species, in particular their clinical pertinence and associated exposure scenarios; e.g., ingestion vs. inhalation. As crustaceans are usually heated prior to ingestion, it can be assumed that these allergens, and, hence, also cross-reactive insect allergens, possess a

given degree of thermostability. For example, allergic reactions in shrimp-allergic patients occur when challenged with blanched mealworm protein (Broekman et al., 2016). The main conclusion to be drawn from this research was that allergies to mealworm with potentially serious outcomes were more likely in patients with allergy to shrimp. It has been demonstrated that heating does not reduce mealworm protein allergenicity, but modifies only protein solubility (Broekman et al., 2015). Another research work, conducted with three distinct mealworm species, has described how the IgE cross-reaction of individuals allergic to crustaceans diminished the mealworm tropomyosin, which was not removed after thermal treatment and *in vitro* digestion (van Broekhoven, Bastiaan-Net, de Jong, & Wichers, 2016).

Conversely to an isolated inhalant allergy to cockroaches and/or mites, allergens that were not treated by heating (dust, feces) led to primary sensitization. The possibility of a cross-reaction with edible arthropods should, therefore, be examined in the used food technology process context; e.g. the cross-reactions of *in vitro* IgE from subjects allergic to house dust mealworm proteins diminish much more than the cross-reacted IgE from subjects who are allergic to shrimp after heat treatment and *in vitro* digestion, but were not removed. Cross-reactive allergens profiles also diverged depending on if subjects were sensitized to house dust mites or shrimp. The conclusion reached was that eating mealworms which had been treated only by heating incurred a risk for those individuals allergic to house dust mites and/or to shrimps (van Broekhoven et al., 2016).

It is generally stated that very few available food technology processes, like hydrolysis and fermentation, are capable of significantly reducing food allergenicity (Verhoeckx et al., 2015). Similar results may be assumed for insect allergens. This implies that new allergen minimization methods need to be developed.

Given the high sensitization potential related with arthropods (e.g. mites, shrimps, cockroaches), it can be assumed that higher intakes of insects or insect-based products will be associated with a rise in the frequency of allergic reactions to insects.

For grasshoppers, several allergies have been reported in relation to them (Paul et al., 2016). The first type can be classified as an occupational allergy, and has been observed in people who have reared grasshoppers, where patients indicated suffering asthma, rhinitis and dermatitis. The second type is an allergy that results from coming into contact with lots of grasshoppers that gather in fields. Here patients indicated asthma. The third category was the allergy that results from eating grasshoppers, where anaphylaxis was observed (Mlcek et al., 2014; Pener, 2014; Yen, 2009). These allergic reactions could be due to the immune system's hypersensitive response to a particular stimulus (Pener, 2014). The aforementioned allergies, which grasshoppers either contain or produce, need to be further investigated in order to study the physiological reaction mechanism in such sensitive individuals to the chemical components that grasshoppers either contain or produce (proteins, etc.).

We summarize some relevant studies in Table 7 about the allergic reactions and cross-sensitivities of edible insects.

5. Legislation

Ensuring the safety of edible insects must be backed by legislation. Insects, as novel food in Europe, must be approved and regarded as safe before being eaten. Insects must be allowed in the marketplace in exactly the same way as conventional food products, and be subjected to the same regulatory requirements that apply to all food types.

In other continents, like Africa and Asia, people have felt traditionally more comfortable with insects' presence in the food chain, but this is not reflected by law, and regulations on insects are either sparse or nonexistent. While local producers of insect-related products can quite easily sell their produce in local markets, exports to industrialized countries could be a challenge if no clear legal framework is in force (Van Hoest, 2017). Nonetheless in the USA, the Food and Drug

Administration (FDA) only mentions insects in the Food Defect Action Levels (FDAL) context, which sets the acceptable level of the defects that a product can contain (Lewis, 2015). Legal uncertainty continues despite several insect-based food products having been commercialized in the USA.

Most developed countries have required no specific regulatory framework because they have not historically eaten insects. Therefore, the existing terminology, if it exists at all, is quite general (De-Magistris, Pascucci, & Mitsopoulos, 2015). General food law principles apply to placing products with insects on the market and, among other things, about good hygiene practices, traceability, compulsory notification, labeling and implementing self-checking systems according to HACCP principles. In Europe, insects are included as novel foods by Regulation 2015/2283EC. However, some European countries have sold insects as a novelty. The EU domestic market requires strictly safe and healthy food. However, these rules for novel foods need updating, as Regulation 2015/2283EC specifies, which includes a demonstration on the history of safety for traditional food from a third country, and of any insect used as food within the EU before 15 May 1997. This regulation, which was passed in November 2015 and came into effect in January 2018, introduced a centralized authorization and an assessment procedure (EFSA, 2016). Currently, all food products on the market have necessitated a novel food dossier since January 2018, while new products need a dossier before being placed on the market. Factors like the culture and origin of the African immigrant population received in recent years, influence whether insects can be accepted as food or not in some countries like The Netherlands, Belgium and France are more tolerant to edible insects for human consumption, and have made risk assessments on insects used as either food or feed. Accordingly, the EU allows individual nations to make their own decisions. Some European countries however, like Germany and France, consume the sugared butterfly wings of the *Zygaena* species and cockchafer (May beetle) soup. Perhaps the main exception is Casu Marzu cheese that is produced in Sardinia (Italy). Its special feature is that flies (*Piophilidae*) lay eggs in its ripening stage inside the cheese, and it becomes riddled with live insect larvae. With time, this cheese becomes soft and weepy because it is infested with insects. The Regional Government of Sardinia passed a regulation by explaining the artisanal Casu Marzu production method (Regione Autonoma della Sardegna, 2014) for it to be recognized as a Traditional Speciality Guaranteed (TSG). This certification (TSG) aimed to certify food products with specific characteristics that differentiate them, but in the same group of products, and that its raw materials have, or its composition or preparation has, been consistently so for at least 30 years. This means that TSG food denominations are registered trade brands with a distinctive function (Tosato, 2013). Casu Marzu was included as a traditional product from the Region of Sardinia in 18 July 2000 and was acknowledged as a TSG. However, it cannot be exported because it is not recognized beyond the Sardegna territory (Belluco, Halloran, & Ricci, 2017). Casu Marzu was still not listed in the EU Database of Origin and Registration as a TSG in July 2014 (<http://ec.europa.eu/agriculture/quality/door/list.html>, accessed in July 2014).

Debate on placing edible insects in European food safety legislation is still underway (Halloran, 2014). Legal barriers in the west have been argued to currently prevent this potential market of insects as food and feed from advancing. Lack of acquaintance with insects as food in the EU could amend the EU resolution as it could imply that people are influenced by neophobia issues and cultural heritage when eating edible insects. The EU also seeks and encourages new enviro-friendly sources of food ingredients, like insects, but also hampers these innovations by enforcing a regulatory environment to protect consumers from the risks of novel food products. In my opinion adopting severe rules should only permit whole insects to be sold, which will not fall in line with new market trends. Therefore, new consumers could refuse to purchase insect food (De-Magistris et al., 2015). To avoid this current situation, a worldwide association called the International Platform for

Table 7
Allergenic potentials of some selected edible insects.

Edible insect	Allergic reaction	Cross-sensitivity	Reference
Sago worm (<i>Rhynchophorus ferrugineus</i>)	Anaphylaxis	–	Yew and Kok (2012)
Yellow mealworm (<i>Tenebrio molitor</i>)	Pan-allergenic	Crustaceans	Verhoeckx et al. (2014)
Yellow mealworm (<i>Tenebrio molitor</i>)	Pan-allergenic	Shrimp	Broekman et al. (2015, 2016)
Bees	Sting	–	Demain, Minaei, and Tracy (2010)
Bee pupae and larvae	Allergic	–	Ji et al. (2009)
Bombay locust (<i>Patanga succinta</i>)	Pan-allergenic	Prawn	Phiriyangkul, Srinroch, Srisomsap, Chokchaichamnankit, and Punyarit (2015)
Locusts	Pan-allergenic	–	Ji et al. (2009)
Arachnids (mites)	Pan-allergenic	Shrimp	Bessot, Metz-Favre, Rame, De Blay, and Pauli (2010)
Cockroaches	Pan-allergenic	Shrimp	Hemmer (2010)
Cochineal (<i>Dactylopius coccus</i> Costa/Coccus)	Hypersensitivity	–	Wüthrich et al. (1997)
Cochineal	Hypersensitivity	–	Dubey et al. (2015)
Cochineal	Hypersensitivity	–	Chung et al. (2001)
Tick larva or tick bite of <i>Amblyomma americanum</i>	Anaphylaxis	Non primate meat	Commins and Platts-Mills (2013)
Mealworm	Pan-allergenic	Shrimp. Dust mites	Broekman et al. (2016)
Grasshoppers	Anaphylaxis	–	Paul et al. (2016)
Grasshoppers	Anaphylaxis	–	Mrcek et al. (2014)
Grasshoppers	Anaphylaxis	–	Pener (2014)
Grasshoppers	Anaphylaxis	–	Yen (2009)
Grasshopper (<i>Mecopoda Elongata</i>)	Hypersensitivity	Shrimp	Leung et al. (1996)

Insects as Food and Feed (IPIFF) has suggested changes to EU laws in recent years to favor more freedom in marketing insects as food.

All the data indicate that European insect consumption is on the rise, but also emphasize a high level of systematic research into the safety and nutritional content of the insects commercially available for human consumption (Payne, Scarborough, Rayner, & Nonaka, 2016).

According to Iglesias (2016), the main EU rules on insects as food are as follows

1. Principle of general food law (Reg. 178/2002): Food shall not be placed on the market if unsafe.
2. Food Hygiene Regulation (Reg. 852/2004), which applies to all food business operators (FBOs) and, therefore, to also keep insects and place them on the market. These acts ensure that general safety, hygiene and traceability requirements apply to insects.
3. Novel Foods (NF) Regulation. According to the new one (Reg. 2015/2283), NF are subject to pre-market approval, with a safety assessment made by either a Member State Food Assessment Body or EFSA.

On 1 July 2017, the use of insect-based proteins in fish feed was allowed in the EU thanks to an amendment to Annex IV of Regulation 999/2001. This new EU regulation 2017/893, published in May 2017 in the Official Journal of the European Union, modified Annex IV of EU Regulation 999/2001 to clearly only permit the use of insect-based proteins in fish feed as of 1 July. Current rules according to EC Regulation (1997) 258/97 were applicable until 31 December 2017. Thus, current rules were applied from 1 January 2018 and applications/notifications can be submitted directly only to the Commission as of this date, which have to comply with new requirements. Besides these applications, which were not finalized by the time the new Regulation came into force, will be governed by the new regulation (Iglesia, 2016). New legislation, i.e. the Novel Foods Regulation (2015/2283), came into force on 1 January 2018. This new regulation will pave the way for a clearer, simpler and more efficient authorization procedure that is fully centralized in the EU, and should enable safe innovative foods to be placed on the EU market more quickly without compromising a high level of public health.

Given growing consumer demand and a pressure consortium, Article 3.5 of EC Regulation 1069/2009, of the European Parliament and the Council, includes the definition of ‘animal’ as: any invertebrate or vertebrate animal. This means that they are governed by ‘general EU feed rules’: consequently, insects are not allowed to be fed with feeding substances, which are prohibited in animal feed, and include particularly manure or slurry, and catering waste from foodstuffs containing fish or meat (the so-called ‘feed-grade materials’, as mentioned above

(IPIFF, 2016). Other regulations on insects have been published; Regulations 2015/2283 Art 3(v) “food consisting of, isolated from or produced from animals or their parts, except for animals obtained by traditional breeding practices, used for food production within the EU before 15 May 1997, and the food from those animals has a history of safe food use within the EU” (IPIFF, 2016).

Nonetheless, there are some law-making conditions that influence the use of insects as food and feed. Currently, the prohibited feed supply in EC Regulation 999/2011 (TSE Regulation) does not approve insect “Processed Animal Protein (PAP)” to be fed to livestock because a safety profile is lacking. Regarding feed/substrate for insects, Annex III to EC Regulation 67/2009 does not permit feeding excrements and separated digestive tract contents, despite these substances being used around the world as substrates in insect production. The legislative structure specifically about insects used as food and feed is, nevertheless, still being developed. In addition, vertebrate’s health and welfare regulations should also concern insects (EFSA, 2015).

The European Commission (EC) proposes the European Food Safety Authority (EFSA) to assess the microbiological, chemical and environmental dangers that arise from producing and consuming insects as food and feed, and to cover the chief steps from the production chain to being used by pets, livestock and humans. The EFSA was asked to draw up an overall opinion based on the above assessment about the potential dangers posed by using insects in food and feed, and in relation to the dangers posed by using other protein origins in food or feed (EFSA, 2015).

The EFSA Focal Points of Member States and EFSA countries were asked to share a present and ongoing danger analysis to test the safety of insects used as food and feed in their countries. Iceland, France, Belgium and The Netherlands answered that they had done a risk analysis of insects used as food or feed (EFSA, 2015). After taking into account the national risk analysis and the EFSA opinion of 8 October 2015, the insect species reared today in the EU that meet the above-mentioned safety state for insect production in feed use are: Yellow Mealworm (*Tenebrio molitor*), Black Soldier Fly (*Hermetia illucens*), House cricket (*Acheta domesticus*), Banded cricket (*Gryllobates sigillatus*), Field Cricket (*Gryllus assimilis*) and Lesser Mealworm (*Alphitobius diaperinus*) (European Commission, 2018). The legislation currently in force needs to be suitably amended so that novel protein sources are not neglected by outdated legislation. Thus, the possibility of developing sustainable food substitutes should be granted to food business operators without dismissing public health protection. It is the responsibility of food business operators (FBO), which market edible insects, to ensure that its products comply with all applicable regulatory and statutory

requirements.

Special concern has been shown by some published studies as, evidently, insects could harbour a bacterium in their gastrointestinal tract that is capable of supporting the horizontal transfer of antibiotic resistance genes (Anacarso et al., 2016; Crippen & Poole, 2009). These antibiotic-resistant genes, such as tetracycline, macrolide, aminoglycosides and vancomycin, have been studied in different edible insects, like mealworms (Osmani et al., 2017) and grasshoppers (Osmani et al., 2017), and in 11 other marketed edible insects (small crickets powder, small crickets, locusts, mealworm larvae, giant waterbugs, black ants, winged termite alates, rhino beetles, mole crickets, silkworm pupae, and black scorpions) (Milanović et al., 2016).

6. Future considerations and conclusions

The consumption of edible insects is popular in Asia and Africa given cultural attributes, as previously discussed in a previous article (Raheem et al., 2019). Insect rearing and processing are still in their infant stages in many European countries. Notwithstanding, there are signs that the consumption of insect-based foods is making its way to Europe and will likely become more acceptable in the future.

In recent years, many insects have been shown to possess very good nutritional profiles and are, thus, good alternatives to other animal protein origins. Insect diversity is very high, and both processing conditions and the rearing practice are expected to modify the nutritional value of end products. During their growth process, more species and specific products are likely to be investigated and optimized for both their nutritional value and deliciousness. Due to the nutritional quality of most edible insects, they will cut GHG emissions and be ecologically relevant when widely consumed as a source of protein. However, there is still a need to bridge knowledge gaps on the welfare of the insects that currently being raised for food and feed (Pali-Schöll, Binder, Moens, Polesny, & Monsó, 2018). The next crucial step will be how to ensure that foods derived from insects are safe and placed on the market legally. As new processing technologies emerge, there will be better opportunities to extract nutritional quality parameters from edible insects for novel food product formulations.

The ecological importance of resorting to insects as a substitute to traditional livestock is expected to be high because it is generally more sustainable to rear insects than conventional livestock. Efficient rearing is expected to be optimized in the future, while more examples of rearing facilities will be evaluated before becoming available. This will provide the basis for more founded discussion on sustainability. One feasible ecological advantage of eating insects is the possibility of rearing them in waste streams. For this to be a feasible option, safety should be guaranteed and legislation must be in place.

One important issue to be contemplated is the safety of edible insects, and some important questions need addressing. For example, can vegetarians consume insects if they are defined as a food of animal origin when accepted as novel food? Then there is the question of the internal microbiome of insects, especially when combined with other food ingredients. What processing techniques are employed to destroy pathogenic organisms? It will be necessary to have critical control points during processing and further tests to ensure no cross-contamination to jeopardize safety. The safety of novel food should be confirmed by compositional data from its continuous consumption for at least 25 years in the daily diet of most inhabitants of a non EU country. The “traditional” concept is not new for European legislation because it is previously defined in Reg. 506/2009 (Art. 2), with specifications varying from 25 to 30 years. Similarly, chemical hazards may be obtained from insects, anti-nutrients and synthesized substances by insects, thus the use of pesticides implies safety concerns. Other important aspects that need to be considered are the bioaccumulation of heavy metals in insects, allergic episodes, allergic cross-reactions and immunomodulatory potentials, which may result when humans are exposed to insects. However, the high diversity of insect species, forms

of farming and substrates suggest that it is impossible to address the security of insects as a whole because of the different risks they may harbor. The previous authorization system, which dates back to 1997, to approve novel food is based on single products, and is an expensive and time-consuming process for applicants and risk assessors alike.

Current EU Novel Food Regulation will harmonize the legislation on using insects as food. Its acceptance by the EU and by other developed countries will speed up insects being accepted as potential protein origin, and will favorably affect research, technology and availability as all insect-based products are regarded as “novel foods”, unless the history of their usage as food before 1997 can be adequately proved and substantiated (Kauppi et al., 2019). These third country producers, sellers and suppliers of insects intended for human use may soon be able to take advantage of EU rules for “traditional foods” from third countries. As previously indicated, entomophagy is common in other countries of the world. The Commission’s suggests novel foods providing a simplified authorization procedure for traditional foods from a third country, which derive from primary production, with a history of safe food use in a third country (Laurenza & Carreño, 2015). Today’s global edible insects tendency obviously shows that novel protein origins should no longer be underestimated by outdated legislation. Finally, the possibility of developing sustainable food substitutes should be granted to food business operators without ignoring public health safety.

Declaration of competing interest

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