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A comprehensive review of entomophagy under legal, historical, safety, and nutritional profile

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With 5 figures

Abstract: In the last decade the use of insects has grown globally in relation to all sectors of the food chain. In about 100 nations around the world, insects are traditionally part of the human diet; this practice is termed entomophagy. Although many studies have been conducted on the importance of edible insects as alternative sources of protein, most of them have focused on consumer acceptance or aversion/neophobia. As human food, insects have various advantages. They are rich in proteins, vitamins, and minerals and can be used in nutrition. Additionally, insects are efficient in bioconverting organic matter into biomass for food, adding the advantage of disposing of some by-products. Insects as foods of the future offer great promise, and their impact is expected to grow as new insights are pursued into quality, cultivation, nutrition, taste and safety. This review aims to be an overview of the laws regulating entomophagy, the history of insect consumption worldwide, safety considerations, and nutrient composition.

Keywords: entomophagy; novel food; Tenebrionidae; Gryllidae; legislation; *Hermetia illucens*

1 Introduction

In approximately 100 nations worldwide, insects have traditionally been an important part of the human diet (Durst 2010) and, recently, entomophagy has gained great interest from both industry and consumers (Nešić et al. 2023). Several international authorities and organizations, such as IPIFF (International Platform of Insects as Food and Feed), NACIA (North America Coalition for Insect Agriculture), AFFIA (Asian Food and Feed Insect Association), and IPAA (Insect Protein Association of Australia), have highlighted insects as future players in the commercial food and feed chain (van Huis 2013; Moruzzo et al. 2021a). Indeed, according to Rabobank, demand for insect protein would rise from 120,000 metric tons to 500,000 metric tons by 2030 (FEEDINFO 2021).

In China and Thailand, industrial-scale farms produce insects for human consumption. In the United States, Canada, and Europe, major companies such as Beta-Hatch (USA), Enterra Feed Corporation (Canada), Oberland Agriscience (Canada), Protix (Netherlands), Agriprotein (Germany), and Ÿnsect (France) raise insects for livestock feed and as a fishmeal replacement. More than 460 patent applications for *Hermetia illucens* (Linnaeus 1758) were published between 2017, and 2022 (https://www.lens.org/), covering rearing procedures, cosmetic and medical applications of its derivatives and agronomic purposes (Franco et al. 2021; Triunfo et al. 2022). Additionally, around 200 patents have been filed for insects as edible sources, with notable growth since the mid-2010 (Kim et al. 2019). The edible insect sector is relatively new, having only been around for about ten years, and its success will require a favourable combination of agricultural research/education, industry, and government support worldwide (van Huis 2022). In development projects, industry and academia frequently collaborate, as in the EU project SUStainable INsect CHAIN (SUSINCHAIN) (Veldkamp et al. 2020) or in the United States, where a Center for Environmental Sustainability through Insect Farming (CEIF) was established (Tomberlin et al. 2022). Meanwhile, significant investments are needed due to the technology used in this sector, that differs greatly from those utilized in the livestock industry (https://www.lens.org/).

The aim of this review is to provide a comprehensive overview of edible insect consumption, addressing the his-

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torical, administrative, legislative, scientific, and psychological aspects related to insect consumption.

2 Worldwide insect consumption history

One third of the world's population is accustomed to eating edible insects (Raheem et al. 2019). Insects have been a regular part of human diets for millennia (FAO 2013). Although some Western cultures are reluctant to consume insects, they have played an important role in the history of human nutrition in Africa, Asia, and Latin America (Bodenheimer 1951). According to Wageningen University "List of the World's Edible Insects", there are 2,111 species of insects consumed worldwide. These include 679 species consumed in the Americas, 524 in Africa, 349 in Asia, 152 in Australia, and 41 in Europe. Traditional insect consumption remains common in underdeveloped nations, as it provides nutritional, economic, and ecological benefits to rural communities (DeFoliart 1999). Many people live below the international poverty line and are unable to access high quality food, which results in undernutrition, especially protein-energy malnutrition, in Africa, Latin America, and Asia. In addition, trends toward 2050 predict a steady population increase to over 9 billion people, which will drive increased food/feed production from available agroecosystems and even greater pressure on the environment (FAO 2017). Despite improvements, alternative foods, especially new sources of protein, must be found to ensure responsive and suitable future food systems.

Globally, the most commonly eaten insects are beetles (Coleoptera) (31%) (Fig. 1), which make up about a third of the total (Costa-Neto 2015). Eating caterpillars (Lepidoptera) is particularly popular in sub-Saharan Africa and is estimated at 18%. Bees, wasps and ants (Hymenoptera) rank third with 14%, most being common in Latin America, followed by grasshoppers, locusts and crickets (Orthoptera) (13%). Next are cicadas, leafhoppers, planthoppers, scale insects, and true bugs (Hemiptera) (10%), termites (Isoptera) (3%), dragonflies (Odonata) (3%), flies (Diptera) (2%), and finally other insects (5%) (Costa-Neto 2015). Hymenoptera are gathered and eaten largely in larval or pupal phases, while Lepidoptera are consumed as caterpillars. Both adults and larvae of coleopterans are eaten, while the Orthoptera, Isoptera, and Hemiptera orders are mostly consumed as mature adults (Raheem et al. 2019).

2.1 Africa

African diets feature a range of wild items, including edible insects (Fig. 2). In Africa, almost 1,500 species of insects are classified as edible (Raheem et al. 2019). The resale value of *Gonimbrasia belina* (Westwood 1849) (mopane worm) in Southern Africa is around $85 million. These caterpillars are found in mopane woodlands in Angola, Botswana, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe (FAO 2003), with Southern Africa harvesting an estimated 9.5 billion mopane caterpillars annually (Raheem et al. 2019). In many African countries, the larval stages of Lepidoptera and winged termites are the most often eaten insects (Illgner & Nel 2000). In Uganda, winged termites and grasshoppers are the most commonly eaten insects (Owen 1973). In Malawi, edible insect larvae are available from mid-October to December when food supplies are running low, whereas in Zambia, caterpillars are a crucial nutrient source from November to February, accounting for 40% of the diet (DeFoliart 1999). Grubs of the palm weevil, *Rhynchophorus phoenicis* (Fabricius 1801), are consumed after frying in western Nigeria and are widely

Fig. 1. Three orders of edible insects most consumed in the World (Jongema 2017).

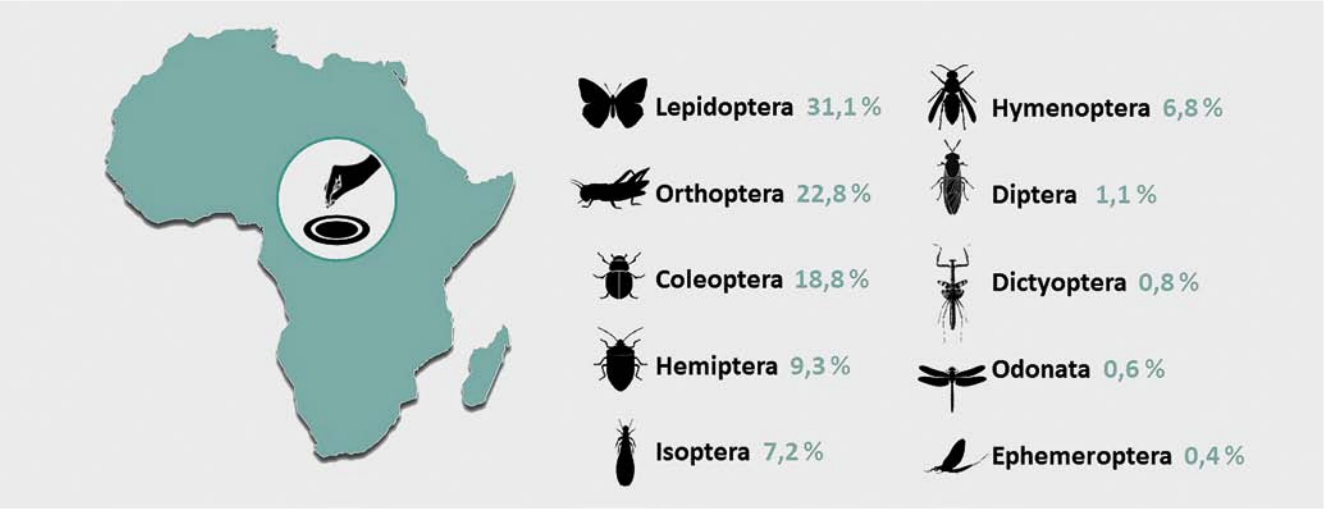

Fig. 2. List of recorded orders of edible insects in Africa. The image shows the percentage frequencies of insect orders considered edible (Jongema 2017).

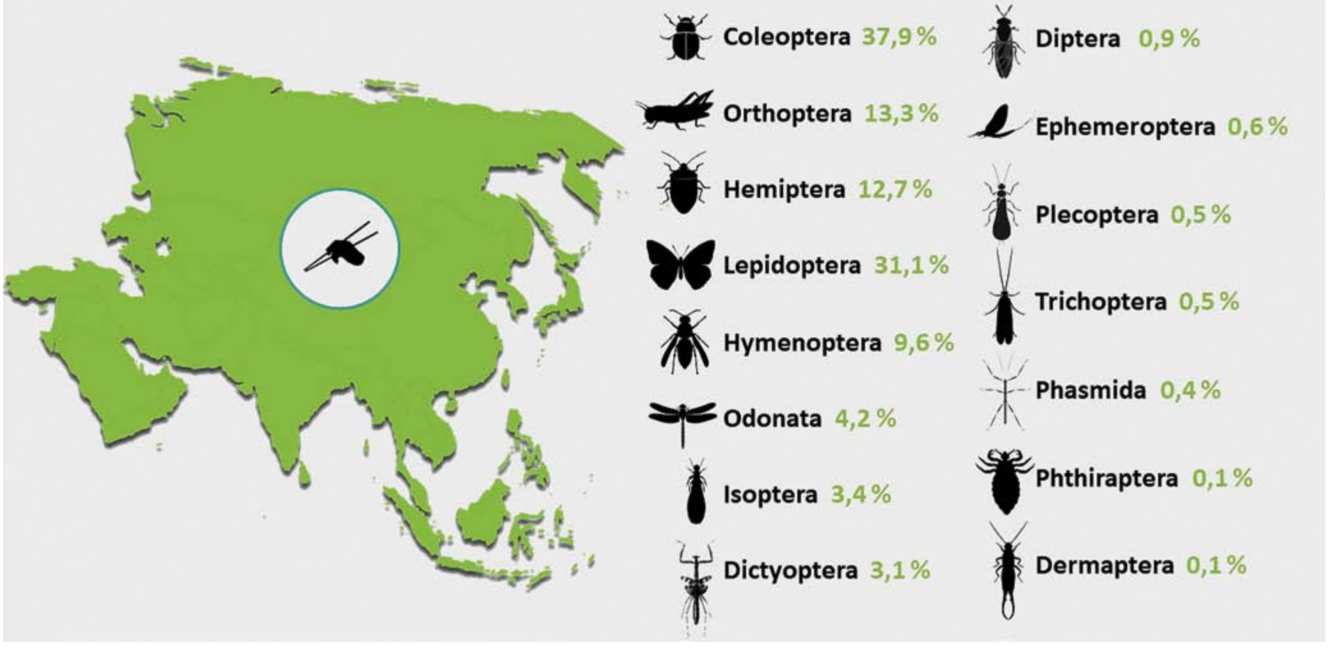

Fig. 3. List of recorded orders of edible insects in Asia. The image shows the percentage frequencies of insect orders considered edible (Jongema 2017).

available in local markets (DeFoliart 1999). In South Africa, insect consumption is common in Mpumalanga, Northwest, Limpopo and Gauteng provinces. Grasshoppers, flying termites, mopane worms, bugs, jewel beetles and white grubs are among the most commonly consumed insects. *Arytaina mopane* (Uhler 1896), *Monomotapa insignis* (Butler 1895), *Sternocera orissa* (Buquet 1835), *Cyrtacanthacris tatarica* (Linnaeus 1758), and *G. belina*, constitute a few examples of the insects that are consumed in Africa (Nonaka & Ethnoentomology 1996).

2.2 Asia

In Asia edible insects are widely consumed. The most regularly eaten categories include beetles, caterpillars, bees, wasps, ants, grasshoppers, locusts, crickets, cicadas, leafhoppers and plant hoppers, scale insects, true bugs, termites, dragonflies, and flies (Fig. 3). In Bangkok, Thailand, 164 species are harvested and sold in marketplaces and supermarkets (Yhoung-Aree & Viwatpanich 2005). Over 20,000 insect farming companies, mostly small local enterprises, are registered in Thailand. Despite a decline in insect consumption globally, it remains prevalent and growing in Thailand, where insects are a "food of choice", often priced higher than chicken, pork, or beef (Yen et al. 2010).

In Japan, at least 117 different species of insects have been used as food throughout history. The orders Orthoptera (22 species), Hymenoptera (17 species), and Lepidoptera (23 species) were the three most important groupings of edible insects in the traditional Japanese diet (Payne 2015). In Japan, traditional meals include insects such as *Oxya yezoensis* (Matsumura 1906), *Oxya japonica* (Thunberg 1815), larvae and pupae of *Vespula lewisi* (Spradbery 1973), and pupae and adults of *Bombyx mori* (Linnaeus 1758). After being cooked with soy sauce and sugar, these insects are packaged and sold (Mitsuhashi 1997). Eating edible insects has a long tradition in China, with 178 insect species widely consumed. In rural China, insects are generally produced and bred for human diet, medical reasons, and animal feed (Zhi-Yi 1997). Grasshoppers, silkworm pupae, wasps, bamboo insects, and stink bugs are among the 20–30 species frequently consumed in restaurants year-round. China also has a robust insect supply chain, including commercial farms and trade routes (Chen et al. 2009). In Korea, insect foods have long been a staple of traditional diets and the government continues to promote their use (Ghosh et al. 2017).

2.3 America

Insects have never been considered part of the traditional American diet, although many species are consumed (Fig. 4). Prior to European colonization, several indigenous tribes in America consumed edible insects as an important part of their diet. Some caribou hunters eat a byproduct of their hunting: the warble fly larvae, large parasitic flies belonging to the genus *Hypoderma* (Latreille 1818) (Schrader et al. 2016). Native Americans in the Great Basin are the most documented consumers of insects (Madsen & Schmitt 1998). Other examples of insect species consumed in North America include *Coloradia pandora* (Blake 1863) (Aldrich 1921), *Cotinis nitida* (Linnaeus 1764) (Sutton 1995), *Anabrus simplex* (Haldeman 1852), and *Camponotus punctulatus* (Mayr 1868). Archaeological finds have revealed evidence of entomophagy in the Great Basin and adjacent regions of California, Nevada, and Arizona (Brickell 1737). Bits of insects were preserved in mummified remains in the Ozark Mountains and Kentucky's Salts Cave (Yarnell 1974). Periodical cicadas of the genus *Magicicada*, which appear in large numbers every 17 years, were eaten in the eastern United States and are still consumed today. The use of this seasonal resource is a unique example of an edible insect that crosses cultural boundaries between indigenous and colonial civilizations (Schrader et al. 2016).

Latin America has a population of over 590 million people, with over 50 million indigenous peoples (Costa-Neto 2015). Insects play an important role in food security and subsistence of the majority of these indigenous people (van Huis 2013). In the northwest Amazon, insects account for about 5% to 7% of total protein consumption throughout

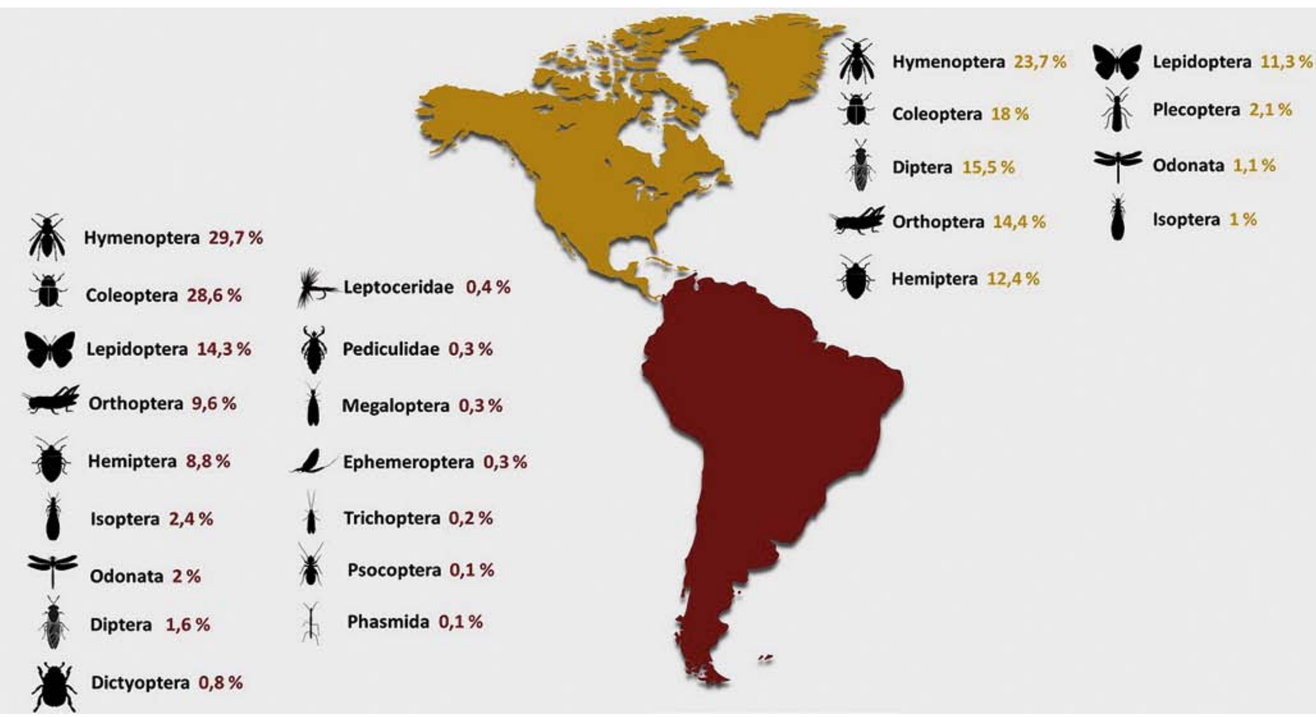

Fig. 4. List of recorded orders of edible insects in America. The image shows the percentage frequencies of insect orders considered edible (Jongema 2017).

the year. During the months of May and June, when availability is at its greatest, their contribution rises to 12–26% (Dufour 1987). The "*escamoles*," along with "*gusanos blanco y rojo del agave*," "*botija*," "*xamues*," "*ahuahutle*", "*axayacatl*," "*vinitos*," and "*avispa negra*", have been a resource for more than 500 years in Mexico (Ramos-Elorduy 2006). The "escamoles" (Dolichoderinae ants of the genus *Liometopum* (Mayr 1861)) were part of the Aztec Emperor Moctezuma's tributes, and their exploitation has continued to this day. The current price for these insects is considerable ($200.00 USD/Kg) due to their exquisite taste and market demand. However, research by inexperienced people, lured by the market value of these insects, has led to a reduction in their renewability, endangering the survival of the species (Ramos-Elorduy 2006).

2.4 Oceania

According to ethnographic studies, insects were once a key element of the diet of Australian Aborigines. More than 60 Australian endemic insect species have been documented as being historically consumed by First Nations people. They included *Melophorus* spp. (Mayr 1862), *Endoxyla leucomochla* (Meyrick 1886), Cerambycidae (Latreille 1802), and *Agrotis infusa* (Donovan 1805) (Fig. 5) (Bodenheimer 1951). During the *A. infusa* harvest season, up to 700 First Nations people gathered in the mountain ranges of the Capital Territory (Brindabella Ranges), New South Wales (Mt Kosciuszko, Bogong Peaks and Tinderry Mountains), and the Victorian Alps. The moths were collected, roasted on hot ash and consumed, allowing for corroborees, feasts, weddings, meetings, and intertribal exchanges (Warrant et al. 2016). The increasing adoption of Western diets by First Nations tribes has led to the decline of historically practiced entomophagy, which is sometimes considered archaic by younger generations (Ponce-Reyes, & Lessard 2021). Insects are considered a growing sector in Australia and, at present, they are a real opportunity to become a major participant in the international edible insect market (Reyes & Lessard 2023). According to AgriFutures Australia, the Australian insect business is an emerging industry with the potential to reach or exceed A$10 million per year in the next five years.

2.5 Europe

Growing or consuming insects is generally seen as taboo in Europe and the Western world in general. In the UK, a Food Standards Agency poll found that only 26% of respondents were interested in trying insect-based food, with men and younger people showing more openness. However, the fact that one-third of the world's population consumes insects, has aroused the interest of industry in Europe and North America. For customers in countries without a tradition of eating insects, the idea is often met with revulsion due to cultural, sociological, and psychological factors. Concerns about safety, potential health risks, and disgust are significant barriers (Skotnicka et al. 2021). A study of a heterogeneous population of Italian respondents found that, although interest in insect meals has grown, consumers still see them as unnecessary and repulsive. The propensity for consumption, based on the various criteria used, appears to be very low (neophobia: 8–24%, insect phobia: 4–21%) (Moruzzo et al. 2021b). However, there are some European countries with an advanced cultural background in this sector, which has made the acceptance of insects easier. Research on the acceptance of which has entomophagy conducted in European countries, such as the Netherlands, has found that people who have eaten insects before have a more positive attitude toward entomophagy (Lensvelt & Steenbekkers 2014).

In Finland, where insect food was authorized in 2018, a study conducted among 212 people aged between 14 and 69,

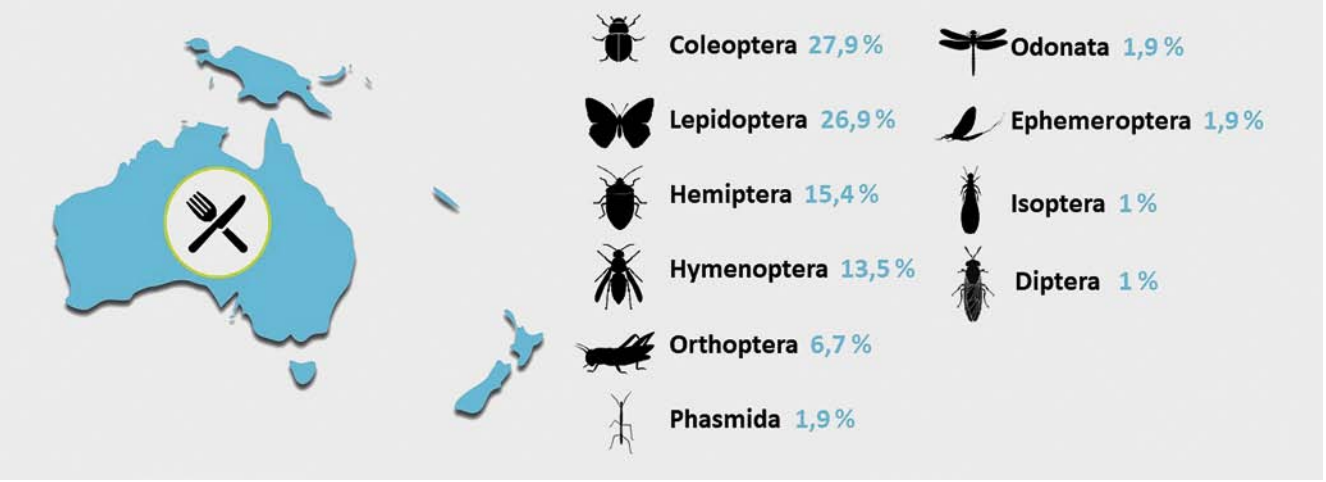

Fig. 5. List of recorded orders of edible insects in Oceania. The image shows the percentage frequencies of insect orders considered edible (Jongema 2017).

showed that younger people (under 30) were more positive about eating insects (71%) compared to older age groups. Acceptability increased when insect cuisine was prepared by a third party, such as a restaurant, or when positioned as a sustainable alternative to high-emission animal proteins. Key factors for consumers included taste, affordability, and perceived sustainability (Halonen et al. 2022). In Hungary, nearly 60% of 400 adult meat consumers were aware of eating insects and those looking to reduce their meat consumption were open to replacing it through the consumption of insects (Gere et al. 2017). In a study conducted on 718 students in Germany, 17.8% of respondents have eaten insects once, 5.3% more than once, and only 0.1% habitually ate insects. *Tenebrio molitor* (Linnaeus 1758), grasshoppers, various insects (flies, maggots), and *Alphitobius diaperinus* (Panzer 1797) were the most consumed insects (Dupont & Fiebelkorn 2020).

3 Legislative point of view

As insect farming gains popularity, concerns about the safety and regulation of their consumption and sale are increasing. In countries where entomophagy is common, there are often no governmental regulations, and they rely on guidance from the World Health Organization (WHO) and the Food and Agriculture Organization (FAO). Conversely, countries without a history of entomophagy but with stringent food safety policies impose stricter regulations on the use of insects as "novel food and feed ingredients". For food purposes, whole insects and insect food products must adhere to basic food legislation principles, including hygiene procedures, traceability, notification, labelling, and a self-control system based on Hazard Analysis and Critical Control Points (HACCP) principles (Halloran et al. 2020).

3.1 Africa

In continents like Africa, where insect consumption is traditionally part of the culinary culture, there are few or no insect laws and regulations. The legal landscape for edible insects in Africa is complex. Nationally, most countries tolerate edible insects without specific legislation. Food law in African countries is shaped by both international and national regulations, with key influences from the African Union and various regional trade blocs. Some countries, such as Benin and Namibia, are interested in establishing legal frameworks for edible insects, while others, like Cape Verde, have explicitly excluded insects from the definition of legal food. Interest in formal regulations exists in countries like Congo-Kinshasa and Niger. Overall, the regulation of edible insects in Africa is still in its early stages (Grabowski et al. 2020).

3.2 Asia

In Japan, novel foods do not require pre-market approval, and the Ministry of Health, Safety and Welfare is responsible for food safety. In China, the Ministry of Health must approve innovative food raw materials. Proteins obtained from insects and silkworm pupae have been accepted as a novel food (Belluco et al. 2013). Thailand, the world's largest producer of crickets, has introduced guidelines for cricket farming (Good Agricultural Practices for cricket farming, Thai Agricultural Standard 8202-2017) to ensure product quality and safety. The standard specifies requirements for farming equipment, feed, water, animal health, environment and record keeping. Feed must be unspoiled, water uncontaminated, clean and sanitized equipment, and all chemicals must be used according to the manufacturer's recommendations (Lähteenmäki-Uutela et al. 2021).

3.3 America

In the United States, the Food and Drug Administration (FDA) regulates insect foods, and in 2013 it stated that insects are considered as food in the Food, Drug and Cosmetic Act (Title 21 of the U.S. Code). Products containing insects must meet FDA regulations, which include bacteriological testing and certification of good manufacturing practices. Wild-collected insects cannot be sold; they must be properly reared. Labels must include the common and scientific names of the insects and any relevant allergy hazards (Lähteenmäki-Uutela et al. 2021). In Canada, novel foods must be approved by Health Canada, to verify their safety and nutritional adequacy before sale (*Canada Gazette Gazette Du Canada Part II* 1999). If a product has been a staple in the diet, a food is not considered novel and can, therefore, be normally consumed. In Mexico, a wide variety of insects are used both as food and for medicinal purposes (Viesca Gonzalez et al. 2009). Food safety is controlled by two government secretariats, SSA (Secretariat of Health) and SAGARPA (Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food). All sanitary products and services are governed by Normas Oficiales Mexicanas (NOMs). In Mexico, there are no insect-specific NOMs yet, but general NOMs apply, such as Norma Oficial Mexicana NOM-251-SSA1-2009 on hygiene standards for food, beverages, and dietary supplements. Moreover, insect foods must indicate the species and life stages involved (Lähteenmäki-Uutela et al. 2021).

3.4 Oceania

Except for indigenous Australians, insect consumption has traditionally been rare in Australia. However, a culture of adapting to insect ingestion has recently emerged (Durst 2010). In Australia, insects for food use are classified as a "non-traditional food," rather than a "novel food", allowing their breeding and sale without specific government legislation or regulation. The Australian Insect Protein Association (IPAA) has developed rules to ensure quality and safety for its members, which are steadily increasing (https://insectproteinassoc.com/). Insect-based foods are classified under Standard 1.5.1 of the Food Standard Code, which covers non-traditional foods whose safety requires further investigation. Before new food can be sold in Australia and New Zealand, they undergo a detailed assessment by Food Standards Australia New Zealand (FSANZ), including evaluation of risk, nutritional value, chemistry and consumption patterns. FSANZ can also grant exclusive authorization for new food or ingredients for 15 months upon request (https://www.foodstandards.gov.au/).

3.5 Europe

In the EU, in the absence of any evidence of significant historical consumption within the European Union prior to 15th May 1997, all insect products are considered "novel foods" under the EU Novel Food Regulation (EU) 2015/2283, and they must be approved by the EFSA (European Food Safety Authority) before being marketed (Regulation – 2015/2283 – EN – EUR-Lex). As a result, before insects for human consumption can be sold in the EU, a license for a "new food" must be secured at the European level. On 1st June 2021, the European Union authorized the marketing of dried *T. molitor* larvae for food use: the first insect to pioneer licensing entomophagy in Europe (Implementing regulation – 2021/882 – EN – EUR-Lex). The second edible insect approved, on 12th November 2021, was *Locusta migratoria* (Linnaeus 1758) (Implementing regulation – 2021/1975 – EN – EUR-Lex). On 10th February 2022, the European Commission authorized the marketing for food use of a third insect, *Acheta domesticus* (Linnaeus 1758) (Implementing regulation – 2022/188 – EN – EUR-Lex). Finally, on 5th January 2023, frozen, paste, dried and powdered forms of *A. diaperinus* were authorised for marketing in the European Union (Implementing regulation – 2023/58 – EN – EUR-Lex). The approval of these four insects, in a relatively short period of time, is a clear signal of change and openness to this new, readily available, high-nutrient food source, which, albeit slowly, is also gaining a foothold in Europe. However, it will be necessary to wait and see the response of consumers. In addition to domestic consumption and production, the EU has enacted legislation regulating the importing of edible insects from countries outside the European Union. Indeed, EU Regulation 2019/626 has established a list of countries authorized to export approved insects in the European Union (Canada, Switzerland, UK, South Korea, Thailand and Vietnam) (Implementing regulation – 2021/1327 – EN – EUR-Lex). Belgium is one of the most advanced countries in Europe in terms of entomophagy. Due to the lack of legal certainty on the scope of the "old" Novel Food Regulation (Regulation (EC) No. 258/97, repealed on 1st January, 2018 by Regulation (EU) 2015/2283), the Federal Agency for Food Chain Safety created a specific law for edible insects, and the Belgian authorities have accepted the marketing of some whole insects for human consumption. This acceptance applied only to ten insect species: *A. domesticus, Achroia grisella* (Fabricius 1794), *A. diaperinus, B. mori, Galleria mellonella* (Linnaeus 1758), *Gryllodes sigillatus* (Walker 1869), *L. migratoria, Schistocerca americana* (Drury 1773), *T. molitor*, and *Zophobas morio* (Fabricius 1775) whose food safety had been assessed in a "shared guidance" statement by the FASFC Scientific Committee and the Board of Health (Common Advice SciCom 14-2014 and SHC No. 9160). On 1st October, 2020, the Court of Justice of the European Union ruled that whole insects are not covered by Regulation (EC) No. 258/97 (Case C-526/19), and, as a result, Belgium' tolerance policy was phased out and replaced with the implementation of transitional measures described in Article 35 of Regulation (EU) No. 2015/2283. Whole insects are not covered by Regulation (EC) No. 258/97, but are now considered "novel foods" under Regulation (EU) 2015/2283. The Dutch Centre for Nutrition has a web page on human consumption of insects (https://www.voedingscentrum.nl/nl.aspx). In Denmark, four Danish universities have set up the consortium INFOOFEE (Danish Consortium on Insects as Food and Feed), composed of researchers and innovators studying the possibilities of using insects as a sustainable source of food and feed from a variety of perspectives. The production and distribution of insects in Denmark is regulated by the Danish Veterinary and Food Administration (DVFA) (https://en.foedevarestyrelsen.dk/). According to Danish law, the use of insects as food for personal use is exempt from the EU Novel Foods Regulation and is, thus, the sole responsibility of the individual consumer. Some insects in the form of whole animals were legally marketed in Denmark, prior to 1st January 2018, with transitional procedures. If an insect was legally placed on the Danish market as food before 1st January 2018, the bug may remain on the market until a decision is made on the application submitted. Furthermore, under the transitional provisions of the Novel Foods Regulation, the following insects that are in the process of being approved in the EU can be marketed as food in Denmark: *L. migratoria, G. sigillatus, A. domesticus, A. diaperinus*, and *H. illucens* (DVFA). In Germany, several edible insect products have also been available on market for some time despite EU regulations. In December 2016, the Swiss Council passed the Edible Insects Act, which allows the sale and consumption of three species: *A. domesticus, L. migratoria*, and *T. molitor*. The requirements of the food agency, the Federal Food Safety and Veterinary Office (FSVO), are strict and complicated. The insects must have been grown for human consumption and must be handled according to food safety guidelines after slaughter. After Brexit, it is unclear whether edible insects will be allowed in the UK. However, the approach of the UK Food Standards Agency (FSA) appears to be challenging. Norway is not a member of the European Union, but it is part of the European Economic Area and, therefore, follows a set of European regulations. Other European nations, many of which are still hostile to welcoming edible insects into their culture, are following the guidelines laid down by the European Union.

4 Nutritional composition of edible insects

Insects have a very high nutritional value, rich in protein, amino acids, fat, carbohydrates, vitamins and minerals. Edible insects, considered as a food source for humans, have a very small carbon footprint, producing fewer greenhouse gases and requiring much less land than conventional livestock like chickens, pigs and cattle (Li et al. 2020). Furthermore, compared with traditional livestock, insect breeding has a higher feed conversion efficiency, or feed conversion rate (FCR), meaning how efficiently feed is converted into biomass, and can be defined as the feed requirement per unit of body weight gain. The high conversion efficiency of insects is due in part to their poikilothermic nature, which means they do not use a significant portion of their energy intake to regulate body temperature (Ramos-Elorduy 2008). Furthermore, up to 80% of a cricket body is edible and digested, compared to 55% and 40% for chicken and pigs, respectively (Nakagaki & DeFoliart 1991); e.g., the gastrointestinal tract, blood, some internal organs, tendons, skin, and bones are some of the by-products encountered in a slaughterhouse (Irshad & Sharma 2015). Taking this into consideration, FCR of *A. domesticus* is twice that of poultry, 4 times higher than in pigs, and more than 12 times higher than in cattle (van Huis 2013).

4.1 Proteins

Dietary proteins are important because they provide the body with the nitrogen and amino acids necessary for synthesizing and maintaining the approximately 25,000 proteins encoded in the human genome, as well as other metabolically active nitrogenous compounds (‘Scientific Opinion on Dietary Reference Values for Protein’, 2012).

A parameter when assessing protein quality is the ratio between essential (E) and not essential (N) amino acids. According to FAO/WHO criteria, the E/(E+N) ratio should reach about 40% with E/N = 0.6 (Belluco et al. 2013). Protein content of insects is high, with many species ranging above 60% (Kouřimská & Adámková 2016), and is influenced by the substrate on which they grow (i.e., vegetables, grains, different kinds of waste). E.g., grasshoppers in Nigeria fed on bran have almost double the protein content of those fed on maize (van Huis 2013), while *H. illucens* larvae grown on spent grain diets had 15% or more protein than those reared on fruit only diets (Scala et al. 2020). The metamorphosis stage can also influence protein content; e.g., *Zonocerus variegatus* (Linnaeus 1758) protein content is about 14.4 and 21.38% for second larval stage and adult, respectively (Ademolu et al. 2010). Studies on protein content of almost 100 edible insects at different developmental stages found that raw protein content ranges between 20% and 70% (Hu Cui 1996; Yang 1998). Orthoptera order (crickets, grasshoppers, locusts) represent the group with the highest protein content: *Melanoplus femurrubrum* (De Geer 1773), *Sphenarium histrio* (Gerstaecker 1884), and *Melanoplus mexicanus* (Saussure 1861) have 77.00%, 71.15–77.00%, and 58.90–77.13% of proteins, respectively (Ramos-Elorduy Blásquez et al. 2012; Rumpold & Schlüter 2013).

Compared to commercial consumed meat, edible insects usually contain more protein; adults of *T. molitor* (24.13 g/100 g) and larvae of *B. mori* (23.1 g/100 g), *G. belina* (35.2 g/100 g) and *T. molitor* (25.0 g/100 g) contain a higher protein content than poultry breast muscle, beef sirloin, and horse meat, all having a protein content ranging from 19.2 g and 21.5g/100g. Concerning amino acid levels, edible insects are a source of complete animal protein, containing all essential amino acids (Orkusz 2021), although most insects have limited levels of either tryptophan or lysine (Bukkens 2005). According to researchers *G. belina, R. phoenicis, Oryctes rhinoceros* (Linnaeus 1758), *Macrotermes bellicosus* (Smeathman 1781), *A. domesticus, Gryllus bimaculatus* (De Geer 1773), *T. molitor, Z. morio*, and *B. mori* show the presence of all the essential amino acids, with levels ranged from 60 mg/100 g for tryptophan to 440 mg/100 g for lysine (Finke 2002; Ekpo 2011; FAO 2013; Siulapwa et al. 2014; Payne et al. 2016; Ritvanen et al. 2020; Orkusz 2021). Insect proteins are also highly digestible (between 77% and 98%), even if, when eating whole insects including exoskeleton, could be less absorbable, due to the presence of chitin (Belluco et al. 2013). The digestibility of insect protein is promising but varies with species and can be improved by chitin removal.

4.2 Fats

Fat is the most energetic macronutrient and facilitates the absorption of lipid-soluble dietary components such as vitamins. Dietary fats include fatty acids, triacylglycerols, phosphatidylcholine and cholesterol, all of which are important for many vital processes in the body. Fatty acids can be classified according to the number of C=C double bonds in the carbon chain: if there are no double bonds they are classified as Saturated Fatty Acids (SFA), if there is just one double bond then they are termed Monounsaturated Fatty Acids (MUFA), and, finally, Polyunsaturated Fatty Acids (PUFA) if there are two or more double bonds (EFSA 2010a).

Fatty acids can also be divided into essential, those that cannot be synthesized by humans and must be obtained in the diet, and those that are not essential. Essential fatty acids include omega-3 (i.e., α-linolenic acid) and omega-6 (i.e., linoleic acid) fatty acids.

Insect fatty acid composition is influenced by the substrate on which they feed (Bukkens 2005). Fat content of edible insects is usually between 10 and 60% of dry matter. Caterpillars are among insects with the highest fat content, ranging from 8.6 to 15.2 g/100 g of fresh insect (Tzompa-Sosa et al. 2014), but also larvae of coleopteran can have high fat content, as reported for *R. phoenicis*, whose total lipid content ranged from 13.9 to 30.5g/100 g of fresh larvae (Fogang Mba et al. 2018); while insects from the Orthoptera order have a relatively low-fat content (3.8 to 5.3g/100 g of fresh insect), with species like *Oxya chinensis* (Thunberg 1815) with only 2.2% of fat on dry matter (Durst 2010). Most edible insects have SFA contents that are usually low (less than 40% of the total fatty acids) (DeFoliart 1991), while they tend to have a higher content of "good fat" like MUFA and PUFA (Kouřimská & Adámková 2016). The average amount of SFA in insect orders ranges from 31% for Hymenoptera to 42% for Isoptera and the two main components of the SFA are generally palmitic acid and stearic acid (Bukkens 1997). In contrast, the average amount of MUFA ranges between 22% for Isoptera and 49% for Hymenoptera (with the oleic acid being usually the predominant MUFA), while PUFA ranges between 16% for Diptera and 40% for Lepidoptera (Rumpold & Schlüter 2013).

Most of the fatty acids in the *H. illucens* larval fatty acid profile are saturated fats, with palmitic acid and lauric acid being the most abundant (Franco et al. 2024).

Oils extracted from *R. phoenicis, Ruspolia differens* (Serville 1838), *Z. variegatus, Macrotermes spp.* (Holmgren 1910) and *Imbrasia spp.* (Hübner 1819), were analyzed and found to be rich in PUFA and MUFA, usually containing essential fatty acids such as linoleic and α-linolenic acids (Womeni et al. 2009). *T. molitor* provides considerable amounts of PUFA, between 21 and 62% of total lipids (Nowak et al. 2016), while the mean PUFA content of the insect order Coleoptera was 27% of total lipids (Rumpold & Schlüter 2013). When compared to traditional meat, insect fatty acids are similar to those of poultry and fish in their degree of unsaturation, while beef and pork contain lower amounts of PUFA (DeFoliart 1991). Furthermore, the presence of linoleic acid is considerably higher in insects, such as *A. domesticus, T. molitor, Z. morio* and *G. belina*, compared to commonly consumed meat (Orkusz 2021).

After triglycerides, phospholipids are the second most abundant group in insect fat, with a content usually less than 20%, parameter that varies according to the stage of life and species (Tzompa-Sosa et al. 2014). Cholesterol generally represents the most abundant sterol in insects, although they vary from low (none in the edible leaf-cutter ant, *Atta cephalotes* (Linnaeus 1758)) to a level similar to animal derived foods (1 mg sterol/g tissue), depending on the species and diet (Ritter 1990). In a study conducted on seven different insects, *A. domesticus* (98 mg/100 g) and *G. bimaculatus* (195 mg/100 g) showed the highest cholesterol content, while the lowest was in *T. molitor* larvae (45 mg/100 g) and adults (51.3 mg/100 g). These values are similar or even higher when compared with traditional meat: a chicken drumstick has a cholesterol content of 84 mg/100 g, while goose carcass contains 32.8 mg/100 g.

In *M. bellicosus* and *G. belina* the average content of cholesterol in the lipid fraction was 3.6% (Ekpo et al. 2009). In addition to cholesterol, other sterols found in edible insects include campesterol, stigmasterol, and β-sitosterol (Sabolová et al. 2016). Insects have a good nutritional fat value and, due to their content of omega-3 and omega-6, could play an important role in supplementing these essential fatty acids in diets.

4.3 Carbohydrates

Carbohydrates represent the primary source of energy in most human diets. Chemically, carbohydrates include dietary fibres, which are nondigestible carbohydrates such as cellulose, hemicellulose, and pectin, that help to maintain normal bowel/colonic function, promote bowel regularity, and ensures a healthy digestive system/function (EFSA 2010b). The chemical classification of carbohydrates is usually based on molecular size and monomeric composition, with three principal groups of sugars (1–2 monomers), oligosaccharides (3–9 monomers) and polysaccharides (10 or more monomers) (EFSA 2010b). While edible insects are rich in protein and fat, they are poor in carbohydrates; however, insects represent a special animal group regarding dietary fibre (Nowak et al. 2016). Indeed, insects contain significant amounts of chitin, an insoluble polysaccharide derived from the exoskeleton of insects (van Huis 2013). The average fibre content ranges from 5.06% for Isoptera to 13.56% for Hemiptera, with maximum yields for *Polyrhachis vicina* (Roger 1863)and *Latebraria amphipyroides* (Guenée 1852) (~29%) (Ramos-Elorduy et al. 1997; Oranut et al. 2010). Among the species with the lowest fibre contents, there are *Aegiale hesperiaris* (Walker 1856) larvae with 0.12% (Melo et al. 2011), *Apis mellifera* (Linnaeus 1758) larvae with 1.00–1.33% (Ramos-Elorduy et al. 1997), and *Brachytrupes* spp. (Serville 1839) with 1.01–11.61% (Banjo et al. 2006; Ramos-Elorduy Blásquez et al. 2012).

4.4 Minerals and vitamins

Vitamins and minerals are essential micronutrients for the normal functioning of the human body and need to be obtained from the diet (EFSA 2022). Depending on the species, edible insects contain different amounts of micronutrients (Orkusz 2021). Edible insects are a good source of iron; e.g., both *G. belina* and *L. migratoria* have a high iron content (respectively, 31–77 mg and 8–20 mg/100 g of dry matter) (Oonincx et al. 2010), and adult insects of *A. domesticus* and *G. bimaculatus* are rich in iron too (Orkusz 2021).

Zinc is also found in edible insects, with an average content comparable with meat: *R. phoenicis* contains zinc at a concentration of 26.5 mg/100 g, more than double the zinc concentration found in beef (Bukkens 2005), while *G. belina* contains 14 mg/100 g of dry matter (Kouřimská & Adámková 2016). Most insects have a similar or higher content of these minerals than in other animal-based foods, thus, offering insect sources of food as potentially useful to alleviate mineral deficiencies (Mwangi et al. 2018). Edible insects also generally contain sufficient amounts of manganese, copper, and potassium (Rumpold & Schlüter 2013). Edible insects are usually low in sodium and can be utilized in low-sodium diets (Rumpold & Schlüter 2013).

Insects contain a variety of water-soluble or lipophilic vitamins (Finke 2002; Oonincx & Dierenfeld 2012), and can be a primary source of water-soluble vitamins of the B group. Dried insects, especially coleopteran like *T. molitor* and *Z. morio*, are rich in riboflavin, pantothenic acid, and biotin, while insects like grasshoppers, crickets, locusts, and beetles are also rich in folic acid (Rumpold & Schlüter 2013). *A. domesticus* have significant B12 vitamin content: from 5.4 µg per 100 g in adults to 8.7 µg per 100 g in nymphs (Kouřimská & Adámková 2016). However, vitamin B12 content is significant in all insect species (Finke 2002; Bukkens 2005). Vitamin C is present in some edible insects, in contrast to meat, where it is totally absent (Orkusz 2021). Anyhow, insects are not a good source of this micronutrient, as it is present only in trace amounts (Kouřimská & Adámková 2016). *Drosophila melanogaster* and *Microcentrum rhombifolium* (Saussure 1859) have significant vitamin E content, with levels of around 11 mg per 100 g of dry matter (Oonincx & Dierenfeld 2012). Significant vitamin E content has been found in other insects, such as larvae of *Rhynchophorus ferrugineus* (Olivier 1790) (35 mg of α-tocopherol and 9 mg of tocopherols β + γ per 100 g of dry matter) (Bukkens 2005), in *B. mori* (9.65 mg of tocopherols per 100 g of dry matter) (Tong et al. 2011), and in *R. phoenicis* (4.76 mg of total tocopherols per 100 g of fresh larvae) (Fogang Mba et al. 2018). *Imbrasia oyemensis* (Rougeot 1955), *Imbrasia truncate* (Aurivillius 1908), and *Imbrasia epimethea* (Drury 1822) contain retinol and β-carotene (vitamin A), with levels ranging from 32 to 48 µg per 100 g of dry matter for retinol and 6.8 to 8.2 µg per 100 g of dry matter for β-carotene (van Huis 2013), while 100 g of *R. phoenicis* fresh larvae can supply up to 67 µg of vitamin A (Fogang Mba et al. 2018).

4.5 Antinutrients

Antinutrients (i.e., oxalates, tannins, alkaloids, phytates and saponins) are natural or synthetic substances that, when taken in high amounts and over a long period of time, impair the bioavailability and/or utilization of nutrients in the human body (Asanga et al. 2015). It is well documented that deficiencies in vitamin B1 (thiamine) can be caused by the heat-resistant thiaminase present in *Anaphe venata* (Butler 1878) larvae, which are ingested as supplementary protein in Africa (Okonji et al. 2012). A 2014 study on *Henicus whellani* (Chopard 1950) reported a level of 9.3, 1.7, 5.3, and 5.2 mg/100 g of oxalates, tannins, saponins, and alkaloids, respectively; so, the presence of these compounds could be a limitation in diets and requires further studies (Musundire et al. 2014). The antinutrient content of the edible termite *M. bellicosus* was quite low (Ntukuyoh et al. 2012), while a recent study conducted on *O. rhinoceros* and *Z. variegatus*, found that antinutrient values are within acceptable limits, indicating that they are good suppliers of macro and micronutrients (Anaduaka et al. 2021). Unfortunately, most studies on the bioavailability and digestibility of edible insects did not include antinutrient compounds, so the overall picture of the interplay between nutrients and antinutrients is unclear and future research should provide more balanced data for a better assessment of edible insect nutritional quality, and, thus, any limitations to consider in terms of consumption.

5 Safety

As the consumption of edible insects is growing around the world, food safety concerns remain. According to the EFSA, the production method, insect species, stage of harvest, and substrates employed in the rearing process influence the concentration of contaminants in insects and insect-derived meals (EFSA 2015). Chemical, biological and allergy considerations are the three types of potential food safety hazards linked with edible insects that need to be more fully documented (Gere et al. 2017).

5.1 Chemical hazards

Insect-derived food products, like those derived from other animals, may include dangerous chemicals. Feed substrates can contain chemical hazards capable of bioaccumulating in insects, including heavy metals and chemicals such as selenium, dioxins, and polybrominated diphenyl ethers (Belluco et al. 2018). Other chemicals, such as biocides to clean facilities and equipment or veterinary medications to treat certain diseases, may also contaminate the insect cultures during rearing and need to be monitored. Contaminants can build up in insects raised for food, posing a risk to human health (EFSA 2015). With respect to the insect species raised on the feed, the substrate may have the largest impact; so, the presence of most chemical contaminants in insects can be controlled by assessments of feeds used to propagate the insects (EFSA 2015).

5.2 Heavy metals

Metals like arsenic, cadmium, lead, and mercury occur naturally and can be present as residues in food due to their presence in the environment and due to human activities. Their accumulation in the body can lead to harmful effects over time (EFSA 2015). Heavy metal concentrations in insects are affected by the feed substrates, the insect species and stage of development (EFSA 2015).

Lead (39.1–455.6 ppm), chromium (38.1–190.5 ppm), and low concentrations of cadmium (0.02–0.21 ppm) were found in *R. differens* from Uganda and were attributed to forages grown in close proximity to significant industrial discharges (Kasozi et al. 2019). High concentrations of lead were also found in dried grasshoppers associated with insect feed in highly polluted mines in Mexico (Handley et al. 2007). Low concentrations (< 0.03 mg/kg) of lead, cadmium, and arsenic were found in a study conducted on *L. migratoria*, bought from various shops in Belgium (Poma et al. 2017). Low levels of arsenic (0.12 mg/kg), cadmium (0.02 mg/kg), and lead (0.73 mg/kg) were reported in edible grasshoppers *O. chinensis formosana* in Korea (Hyun et al. 2012). Mercury, lead, cadmium, and arsenic were found in low concentrations in *B. mori, Holotrichia spp.* (Hope 1837), *A. domesticus*, and *Patanga succincta* (Johannson 1763) in Thailand. In detail, *Holotrichia spp.* had the highest levels of arsenic and mercury, with 0.576 mg/kg and 0.08 mg/kg, respectively, *A. domesticus* had the highest lead level of 0.155 mg/kg, while all the insect samples had cadmium levels less than 0.05 mg/kg. Anyhow, all these species contained heavy metals at concentrations well below maximum legal values (Köhler et al. 2019). The amounts of three different heavy metals (mercury, cadmium, and lead) in grass and four insects (*Calliptamus italicus* (Linnaeus 1758), *Oedipoda caerulescens* (Linnaeus 1758), *Oedipoda germanica* (Latreille 1804), and *Chorthippus* (*Glyptobothrus*) *crassiceps* (Ramme 1926)) that feed on grassland were studied (Devkota & Schmidt 2000). Heavy metal concentrations in both the grass and insect samples were in the order: lead > cadmium > mercury. Cadmium concentrations were 2–4 times greater in all four grasshopper species studied than in the grass, and the amount of lead in the grass was lower than in the four grasshopper species. Mercury levels were two times greater in *C. crassiceps* than in grass, but mercury levels were lower than cadmium and lead levels (Devkota & Schmidt 2000). This study demonstrates the possibility of heavy metal bioaccumulation in insects that fed on contaminated substrates. In the study of Kolakowski et al., nineteen samples of edible insects (fifteen from cricket, four from silkworm) contained detectable arsenic, with varied values from 0.030 mg/kg (whole silkworm pupae) to 0.34 mg/kg (cricket powder), with an average of 0.094 mg/kg. Furthermore, cadmium was absent in all silkworm samples, but detected in all cricket samples with levels ranging from 0.031 to 0.23 mg/kg, with an average of 0.083 mg/kg; lead was present in 52% of the samples with concentrations from 0.019 to 0.059 mg/kg, with an average of 0.034 mg/kg; mercury in 93% of cricket samples but in none of the silkworm samples, with levels from 0.00094 to 0.028 mg/kg, with an average concentration of 0.0062 mg/kg (Kolakowski et al. 2021).

5.3 Veterinary drugs and hormones

Veterinary medication residues (antibiotics, hormones) in substrates such as manure may end up in insects and their products. Moreover, antimicrobials or other veterinary medications can be used in insect breeding (EFSA 2015). Furthermore, veterinary medications may be sprayed or mixed with substrates to battle insect diseases, and this use may leave residues in insects. Data on veterinary drug residue and hormones in edible insects are scarce. Several veterinary drugs including salicylic acid, metoprolol, paracetamol, and nicarbazin were detected in *T. molitor, L. migratoria, A. domesticus*, and *H. illucens* (de Paepe et al. 2019). Paracetamol and structural analogues are widely distributed and accumulated in aquatic environments (Wu et al. 2012) and were detected in various insect samples below the Screening Detection Limit (SDL), while metoprolol tartrate, a commonly detected drug in drinking water (van den Brandhof & Montforts 2010) and nicarbazin, a commonly used antibiotic frequently found in manure were found in concentrations higher than the SDL (de Paepe et al. 2019).

5.4 Pesticide residues

Pesticides are plant protection products that contain at least one active substance. According to EFSA, pesticide residues may pose a risk to public health (EFSA 2015). Edible insects absorb pesticides from plants growing in herbicide-treated areas (Saeed et al. 1993). Edible locusts in Kuwait contained chlorinated pesticides and unusually large quantities of the phosphorus-containing pesticides sumithion (740 µg/kg) and malathion (49.2 µg/kg) (Saeed et al. 1993). The presence of 511 pesticides in edible crickets and silkworm was investigated and detected in 89% of the crickets and 50% of silkworms-based products, with most of the positive samples containing just one pesticide residue, and glyphosate being the most frequently detected (Kolakowski et al. 2021). Edible insects in Togo were assessed for pesticide residues, and they were not found in *Brachytrupes membranaceus* (Drury 1770), *Rhabdotis sobrina* (Gory & Percheron 1833), *Gnathocera impressa* (Olivier 1789), *Gnathocera trivittata* (Swederus 1787), or *Cirina forda* (Westwood 1849), while desethylatrazine was found in *Acanthacris ruficornis* (Fabricius 1787) (0.320 µg/kg), *Oryctes monoceros* (Olivier 1789) (0.217 µg/kg), and *M. bellicosus* (0.532 µg/kg) (Badanaro & Dué 2022). Diuron was found in the latter species, while the insecticide permethrin was exclusively found in the species *R. phoenicis* (0.556 µg/kg). Multiple pesticide residues have not been found in the investigated species, and, therefore, the studied species have a low tendency to bioaccumulate pesticides (Badanaro & Dué 2022). The accumulation of pesticides varies depending on the insect species, their developmental stage, the pesticide dosage in the feed or environment, as well as whether the insects were caught in the wild or farmed. Overall, pesticides in edible insects do not appear to constitute a significant human health risk, while monitoring for safety is still the key (Kolakowski et al. 2021).

5.5 Toxins produced by insects

Plant poisons can be sequestered by some insect species, making them less appealing to predators, such as for glucosinolates in *Murgantia histrionica* (Hahn 1834) (Aliabadi et al. 2002). Other insect species are able to produce toxins themselves, such as Tenebrionidae family insects that can produce (benzo)quinones and alkenes (Crespo et al. 2011) or moths of the *Zygaena* genus, which can produce cyanogenic glucosides that release cyanide when degraded (Zagrobelny et al. 2009). Venomous insects are categorized into two groups: phanerotoxics and cryptotoxics. As with bees and ants, phanerotoxics have organs for the synthesis and delivery of venoms. In most cases, these chemicals are inactivated in the digestive tract. Cryptotoxic insects lack an external secretary mechanism and become toxic only after being swallowed. Toxins may be present in cryptotoxic insects, and these compounds might be concentrated in certain structures or distributed throughout the body (EFSA 2015). According to EFSA, for *Musca domestica* (Linnaeus 1758), *H. illucens, T. molitor, Z. morio, A. diaperinus, G. mellonella, A. grisella, B. mori, A. domesticus, G. sigillatus, L. migratora migratoriodes*, and *S. americana* (insect species identified as having significant potential for use in food and feed in the EU), there are no immediate indications that they excrete reactive, irritating, or toxic substances (EFSA 2015).

Some researchers used repeated dose toxicity experiments, ranging from 250 to 3,000 mg/kg body weight per day, in rats to assess the safety of edible insects such as *Allomyrina dichotoma* (Linnaeus 1771) larvae (Noh et al. 2015) and *T. molitor* (Han et al. 2016). A complete toxicological assessment, including hypersensitivity assays, was performed and no treatment-related side effects were found. Furthermore, the freeze-dried powder of *T. molitor* showed no genotoxic effect in vitro and in vivo (Han et al. 2016). The lack of genotoxicity in vitro was also confirmed for water soluble extracts of *Z. variegatus* and *Oryctes boas* (Fabricius 1775), even though both extracts indicated some oxidative stress in vitro (Memiş et al. 2013). It is also reported that traditional edible insects consumed in China are safe, nontoxic, and have potential as novel food resources (Gao et al. 2018).

5.6 Polycyclic aromatic hydrocarbons (PAHs)

PAHs (Polycyclic Aromatic Hydrocarbons) are a wide group of chemical molecules that include two or more fused aromatic rings, typically produced by the incomplete combustion or pyrolysis of organic matter, or through industrial processes. Some of them can cause cancer and be genotoxic (EFSA 2008). Data available for PAHs contamination in edible insects are scarce. PAH concentrations in *M. domestica, H. illucens*, and *Calliphora vomitoria* (Linnaeus 1758) ranged from 0.28 to 9.82 µg/kg for PAH4 and < 0.05 to 2.2 µg/kg for benzo(a)pyrene, all of which are carcinogenic or potentially carcinogenic (Charlton et al. 2015). The presence of PAHs in *M. bellicosus* and *C. forda* from Togo was assessed for both raw and processed samples (Badanaro & Dué 2022). *M. bellicosus* did not contain any PAHs. Raw *C. forda* was also PAH free, while processed *C. forda* contained only fluoranthene (classified as substance of very high concern due to its persistence, bioaccumulation and toxicity by the European Chemicals Agency) among the eight PAHs investigated, but at a concentration (0.31 µg/kg) well below the legal limit allowed in food (1 µg/kg) (Badanaro & Dué 2022). In conclusion, the consumption of edible insects studied by the researchers in Togo does not present a risk of contamination with PAHs (Badanaro & Dué 2022), while, according to other researchers, some insect-cooking techniques adopted in Africa may pose a carcinogenic danger due to the presence of toxic substances (like PAHs) that may be generated by chemical interactions between the insects and other ingredients, such as acrylamide, furans, chloropropanols, and heterocyclic aromatic amines (van der Spiegel et al. 2013).

5.7 Biological hazards

Since there is a significant evolutionary gap between humans and insects, insect pathogens are often exclusive to invertebrates and do not affect vertebrates (Eilenberg et al. 2015).

According to EFSA, there are two types of microbiota associated with the consumption of edible insects to be considered as potential hazards: those intrinsically linked to insects as part of their lifecycle and those introduced during farming and processing. Moreover, the risk of infection posed by human ingestion of insects and their products is influenced by the feed and the processing methods adopted during farming, storing, and consumption (EFSA 2015).

5.8 Bacteria

Arthropods are well known vectors for bacteria, such as *Salmonella*, and insects, such as flies, can acquire and spread *Salmonella* (Holt et al. 2007). Also, *Campylobacter* has been isolated from insects such as beetles and flies in contact with infected poultry; however, based on experimental conditions, it has been reported that *Campylobacter* can only survive for a limited time in insects (EFSA 2015). The Belgian Federal Agency for the Safety of the Food Chain's Scientific Committee published a report on the microbiological state of insects raised especially for food production, including *T. molitor, L. migratoria* and *Z. morio*: high values of 10^7 cfu/g were reported for total aerobic bacterial, anaerobic count, and Enterobacteriaceae. For *B. mori*, lower levels (< 10 cfu/g) for Enterobacteriaceae were measured (FASFC 2014). A 2011 study in Africa found harmful microbes in the larva of *Bunaea alcinoe* (Stoll 1780), including *Staphylococcus aureus, Bacillus cereus, Proteus*, and *Escherichia coli* (Braide et al. 2011). Other human pathogenic bacteria such as *Vibrio, Streptococcus, Staphylococcus, Clostridium* and *Bacillus* were found in a study assessing the microbiota diversity present in edible insects processed and sold in Thailand (Osimani et al. 2017). A recent study that characterized microbes in *R. differens* collected in the wild in Uganda also suggested that edible insects could harbour potentially harmful bacteria genera; *Campylobacter, Bacillus, Staphylococcus, Neisseria, Pseudomonas*, and *Clostridium* bacteria were identified (Ssepuuya et al. 2019). According to a survey on the microbiological status of 55 freeze-dried insect-based products conducted in Europe, more than half (59%) were above the process hygiene standard of 10^6 cfu/g for aerobic bacteria in raw materials used in meat preparation (NVWA 2014). The threshold of 10^3 cfu/g for Enterobacteriaceae in raw materials used in meat preparations was also exceeded in 65% of cases. *Clostridium perfringens, Salmonella*, and *Vibrio* were not found in the samples, while *B. cereus* was less than 100 cfu/g in 93% of the samples (NVWA 2014). EFSA states that microorganisms may be present in non-processed insects depending on the feed and conditions for production. Active reproduction of pathogens in the digestive tract of insects does not appear to be a concern, thus incidence of contamination will likely be lower than in other non-processed sources of animal protein and any risk of transmission can be reduced by processing (EFSA 2015).

5.9 Viruses

Most insect viruses are species or family specific, meaning they are only harmful to invertebrates and not to human or other vertebrates (EFSA 2015). However, insects can act as replicative vectors for viruses that infect vertebrates. Arboviruses are arthropod-borne viruses that cause disease in humans (such as dengue fever, West Nile fever, Rift Valley fever) (King et al. 2012). They also reproduce successfully in mosquitoes and midges. As a result, these viruses can successfully proliferate in both vertebrates and invertebrates crossing species barriers. However, there is no evidence that such viruses occur in food and feed insects (EFSA 2015). Insects can also be passive vectors of human and livestock viral diseases (Sawabe et al. 2006). However, insect pathogenic viruses found in food and feed insects are peculiar to insects and are, therefore, not considered a threat to vertebrate animals or humans. Viruses of vertebrates can persist in substrates and be taken up by insects produced for food or fed via the substrate. The risk of transmission can be reduced by selecting the appropriate feed and proper processing (EFSA 2015).

5.10 Parasites

The risks from parasites depend on environmental conditions and feed substrates (EFSA 2015). Parasites belonging to the families Lecithodendridae and Plagiorchidae could be transmitted orally (Chai et al. 2009). A parasite that could be transmitted to humans by edible insects (such as ants) is *Dicrocoelium dendriticum* (Boye et al. 2012). Other parasites found in edible insects include protozoa, such as *Entamoeba histolytica* and *Giardia lamblia*; they are found in cockroaches as possible foodborne and waterborne diseases, *Toxoplasma* spp. in *Periplaneta americana* (Linnaeus 1758) and *Blattella germanica* (Linnaeus 1767), and *Sarcocystis* spp. (Graczyk et al. 2005). Another example of how insects can act as vectors is trypanosomiasis. According to the World Health Organization (2010), around 10 million people in the Americas are infected with Chagas disease (also known as American trypanosomiasis), and over 10,000 people die annually. Infection has been linked to the inadvertent eating of insects or the consumption of contaminated food (Pereira et al. 2010). Although there are parasites in insects linked to sporadic human parasitic disease, there is little data on parasites found in farmed insects. A properly maintained closed farm setting would lack the hosts required for parasite life cycles to be completed and adequate management prior to consumption, such as freezing and boiling, can further reduce any possible hazards (EFSA 2015).

5.11 Fungi

Insects can carry entomopathogenic fungi, that generate insect-specific toxins but are generally safe for vertebrate animals, including humans (EFSA 2013). In rare cases, diseases caused by entomopathogenic fungi are encountered in immunocompromised people (Roberts & st. Leger 2004). Yeasts and fungi were found in fresh, freeze-dried, and frozen *T. molitor* and *L. migratoria* (FASFC 2014). Mycotoxins, harmful secondary metabolites produced by fungi, are resistant at ordinary food preparation temperatures and can be present in insect feed (Imathiu 2020). High levels of aflatoxins were found in several commercial lots of *G. belina* highlighting the importance of proper processing and storage in order to avoid contamination (Durst 2010). Mycotoxin-forming fungus from *Aspergillus* spp. and *Penicillium* spp. were identified in the substrate and insect body of *G. sigillatus* industrially farmed for human consumption (Vandeweyer et al. 2018). A 2017 study showed that in *Gynanisa maja* (Klug 1836) (11 μg/kg), *Gonimbrasia zambesina* (Walker 1865) (12 μg/kg), and *Macrotermes falciger* (Gerstäcker 1891) (24 μg/kg), average aflatoxin concentrations were above regulatory limits (10 μg/kg) (Kachapulula et al. 2018). These findings clearly suggest that edible insects can contribute to aflatoxicosis, but, in general, EFSA stated that these risks can be managed by proper hygienic measures in the production chain (EFSA 2015).

5.12 Prions

Prions are infectious agents causing fatal conditions affecting the brain and the nervous system, such as bovine spongiform encephalitis, scrapie, and Creutzfeld-Jakob disease (Mézes & Erdélyi 2020). EFSA identifies three potential prion-related risks with insects: insect-specific prions, insects as mechanical vectors of animal/human prions, and insects as biological vectors of prions (EFSA 2015). Since insects lack prion-encoding genes, prion proteins cannot be naturally expressed in these hosts. Prions from mammals cannot multiply in insects, and, as a result, insects are not thought to be biological vectors or amplifiers of prions (EFSA 2015). In conclusion, based on the available information, insects farmed on a feed or in an environment containing infectious prions could act as mechanical vectors of infection, posing a risk of prion disease transmission through food, but, since mammalian prions cannot replicate in insects, the quantity of infectivity contained in the feed will determine the overall prion infectivity transported by insects (EFSA 2015).

5.13 Allergy hazards

Food allergies represent an adverse immune response to food allergens and can lead to severe consequences (Imathiu 2020). Although solid epidemiological data on food allergies to edible insects is lacking, cross-reactivity, particularly with crustaceans, has been identified as a significant concern. This is due to the presence of shared allergens such as tropomyosin, arginine kinase (AK), aspartic protease, hemocyanin, glutathione S-transferase, troponin C, myosin light chain, serine protease, and a-amylase (Ribeiro et al. 2021). Primary sensitisation (either through environmental or occupational exposure) has also been linked to allergic reactions to edible insects (Pomés et al. 2017). The intake of *G. belina* has been connected to a few cases of anaphylactic shock (Okezie et al. 2010). In a Belgian study, 19% of participants showed sensitization to the tested insects (Francis et al. 2019). In China it was estimated that up to 18% of fatal reactions to foods were linked with insect consumption (Ji et al. 2009), while in Laos 7.6% of insect consumers experienced allergic reactions (Barennes et al. 2015). In Asia, AK was identified as the most common allergen in *B. mori* pupa (Liu et al. 2009), and, during 2010–2019, allergens were responsible for 25% of the identified hazards in edible insects. According to EFSA a potential approach might be to list the insect protein as well as the potential allergenicity or cross reactivity on the product label. Allergens in edible insects appear to be resistant to thermal treatment and enzyme digestion, which is similar to the behaviour of crustacean allergens (Ribeiro et al. 2021). In conclusion, allergies to crustaceans (due to cross-reactivity) and people who are regularly exposed to edible insects are the two largest risk categories for developing food allergies to insects (Ribeiro et al. 2021).

6 Conclusions

Although the consumption of insects is part of the history of many of the world's populations, some cultures remain strongly reluctant to adopt this practice. However, edible insects can be a promising resource to address global challenges of food security and sustainability. To make insect consumption more common and safe, in addition to researching sustainable farming practices and scalable production methods, strong safety standards and regulations need to be established to ensure the health and safety of consumers. Additionally, a comprehensive nutritional profile of various insect species needs to be developed to fully understand the benefits and potential risks related to consumption. Finally, cultural acceptance and consumer perceptions need to be studied to develop effective strategies for the promotion of insect-based foods. Addressing these challenges will pave the way for the integration of edible insects into mainstream diets around the world.

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