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Edible insects and food safety: providing scientific insights for the agro-food sector

Teresa Bento de Carvalho, Paula Teixeira and Joana Bastos Barbosa

Universidade Católica Portuguesa, CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Rua Diogo Botelho 1327, 4169-005 Porto, Portugal

ABSTRACT

The agri-food industry would greatly benefit from a solution based on a sustainable approach inspired by the Farm-to-Fork strategy to fulfill global food demands for primary foodstuffs. Entomophagy has all the potential to answer the cornerstones of the 2030 Agenda for Sustainable Development. From a nutritional standpoint, insects are emerging as a high-protein meat alternative, with many edible insects having nutritional profiles similar to other commonly eaten plant and animal products while having the potential to be a more sustainable and ecologically friendly source of nutrients for humans. However, safety concerns remain underexplored, including microbiological, allergenicity, and chemical risks. Furthermore, regulatory frameworks, such as Regulation (EU) No 2015/2283 on novel foods, continue to evolve but exhibit significant gaps in addressing the complexities of insect-based food products. Public perception and cultural acceptance also pose additional challenges. Therefore, this review examines the edible insects' potential but addresses key obstacles to their integration into human diets. Particular focus is given to the safety and regulatory challenges that must be overcome to ensure consumer confidence. By fostering a better understanding of entomophagy's benefits and risks, this work aims to support its adoption as a viable strategy for enhancing sustainability and food safety in the global agri-food sector.

KEYWORDS

Entomophagy; food safety; protein alternatives; sustainability

Introduction

According to United Nations projections (United Nations Department of Economic and Social Affairs Population Division 2024), the world's population is predicted to rise from 8.2 billion in 2024 to a peak of about 10.3 billion by the 2080's. This anticipated rise in population highlights the ongoing challenges related to resource management, sustainability, and infrastructure that nations must address. As the global population grows, the demand for food, water, and energy is expected to rise significantly, calling for innovative and sustainable solutions to meet these needs (Cadinu et al. 2020; Fuso et al. 2024; Gałęcki, Bakuła, and Gołaszewski 2023). The Food and Agriculture Organization (FAO) forecasts that by 2050, we will need to produce 60% more food to meet global demand (Food and Agriculture Organization of the United Nations (FAO) 2023). To address this impending food security challenge, there has been a notable resurgence of interest in entomophagy, particularly in Western cultures. This renewed interest is evidenced by the significant rise in academic publications on the subject; from 1977 to 2012, a search for “entomophagy” on Scopus database yielded 67 results, whereas from 2012 to 2024, 942 were retrieved.

Entomophagy could make a significant contribution to the Farm to Fork strategy to make food systems fair, healthy and sustainable (Gałęcki, Bakuła, and Gołaszewski 2023).

Edible insects provide essential nutrients such as protein, fat content, fiber, amino acids, vitamins, and minerals, offering high nutritional value and a sustainable and ecologically friendly alternative to meat (Baiano 2020; Nowakowski et al. 2022; Zhou et al. 2022). Additionally, they are a source of protein with high digestibility (Pilco-Romero et al. 2023) and have high bioavailability and solubility of minerals, including iron (Fe), calcium (Ca), phosphorous (P), potassium (K), among others (Ordoñez-Araque, Quishpillo-Miranda, and Ramos-Guerrero 2022). Regarding vitamins, insects have been found to be a good source of vitamin B, namely, B2 and B12, vitamin E and vitamin C (Orkusz 2021). Edible insects have been proven to be an excellent source of dietary fiber to the detriment of meat, which does not contain any fiber (Orkusz 2021). Insect rearing requires less arable land and water, offers a better feed conversion ratio, and produces significantly less greenhouse gas emissions than traditional livestock. By sourcing insect feed from organic waste streams, this approach aligns with the circular economy principles, contributes to the economic feasibility of the rearing process and supports sustainability (Hammer et al. 2023; Nowakowski et al. 2022). Entomophagy can contribute to the United Nations Sustainable Development Goals, ensuring food safety, economic growth, equitable market access, and social insertion.

With close to 2000 insect species recognized as edible, belonging mainly to the orders Blattodea, Diptera, Hemiptera, Hymenoptera, Coleoptera, Lepidoptera, Odonata and Orthoptera (Liceaga 2022), the consumption of insects has been a common practice in various parts of the world (i.e., Central America, Asia, South America, Africa, and Australia) (Giampieri et al. 2022) with archaeological evidence and historical records suggesting that insects have been part of the human diet since early hominids, playing a crucial role in the traditional gastronomy of a myriad of cultures (Liceaga 2022; Olivadese and Dindo 2023). Examples of traditional uses can be found in the literature. In Thailand, street markets offer fried crickets and grasshoppers as popular snacks. There, these insects are highly valued as affordable sources of protein and have been a common practice for decades (Hanboonsong and Durst 2014). In Sub-Saharan Africa, mopane caterpillars are widely consumed, particularly in southern Africa, with significant popularity in Botswana and Zimbabwe. These caterpillars are dried and stored for future consumption, providing an important source of nutrients during times of scarcity (Van Huis 2013). In Latin America, more specifically in Mexico, *chapulines* (grasshoppers) are a traditional delicacy, particularly in the states of Oaxaca and Puebla. Insects are typically seasoned with lemon, garlic and chili, as reported by Van Huis (2013). Nonaka (2009) highlights entomophagy practices in Japan, particularly the common consumption of wasps in the Japanese Alps, where some communities even host festivals dedicated to catching and preparing wasps as local delicacies. In Oceania, Meyer-Rochow (2010) reports that Australian Aboriginal communities include witchetty grubs (moth larvae), traditionally roasted over hot coals or eaten raw, as part of their ancestral diet. This traditional knowledge, when supported by a history of safe consumption, is paramount to define which insects will not pose a hazard to human health and which processing methods are adequate for insect rearing destined for human consumption (Belluco et al. 2015). Nonetheless, the disgust factor in Western cultures remains a significant barrier to the acceptance, introduction and integration of edible insects into our diets (Ribeiro et al. 2022).

As scientific, industrial and economic expertise in insect rearing is still in its infancy, there are significant challenges to rearing insects for food production (Cadinu et al. 2020). Consumption should be cautiously approached, and potential adverse reactions require ongoing monitoring and evaluation. While insects are a promising alternative protein source, further research and regulatory measures are needed to ensure their safety as food.

To date, European legislation is not definite regarding the use of insects as food products (Regulation (EU) No 2015/2283), as the Novel Food Law is general and applies to all novel foods. The same is observed for the USA and Canadian novel food legislation, which only mentions that insects must be reared specifically for human consumption and comply with Current Good Manufacturing Practice Regulations (U.S Food and Drug Administration (FDA) 2023) and Safe Food for Canadians Regulations (SFCR) (Canadian Food Inspection Agency (CFIA) 2021). In the

absence of an international regulatory body for the introduction of edible insects into daily habits, the challenge to develop standardized practices and quality assurance measures remains, and dissonant laws and regulations between countries make the export/import of these products as well as the analysis of their market value difficult (Lähteenmäki-Uutela, Marimuthu, and Meijer 2021).

Studies on the safety of insects as food are scarce and microbiological, chemical, and allergenicity risk evaluation needs further investigation. The presence of pathogens directly associated with the insect microbiota that will carry over into the final product has been reported to be the most prominent microbiological risk associated with entomophagy (Bessa et al. 2020; Schlüter et al. 2017). Thus, suitable processing mechanisms after harvesting are necessary and will influence the quality and safety of the products (Megido et al. 2017). Also, chemical and toxicological risks can originate from either contamination or metabolites produced by the insect. Chemical hazards vary greatly with species, growth/farming conditions, rearing substrate, and feed (Baigts-Allende and Stathopoulos 2023). Similarly, taxonomic relations between novel protein sources must be studied and related to well-known allergens to understand their allergenic capacity, as cross-reactivity with crustaceans or other arthropods may possibly elevate the allergenic risk of insect-based foods (Ribeiro et al. 2018). Thus, assessment of microbiological, toxicological, and allergenic hazards must be considered when selecting insect species, development stage, feeding conditions and hygiene conditions of the farming facilities to avoid the presence of pathogenic bacteria, toxin production, antinutrients, allergens, amongst others (Baigts-Allende and Stathopoulos 2023; Schlüter et al. 2017). According to the World Health Organization, unsafe food causes millions of cases of foodborne disease and thousands of deaths worldwide (World Health Organization 2015). However, foodborne diseases are preventable with effective control strategies, whereby more studies are needed to diminish the knowledge gap on the safety of insects as food.

The aim of this review is to approach the topic of entomophagy from a comprehensive food safety perspective, providing insight into the entomophagy world and insect-based food. Alongside the sustainable foundation of this practice, understanding the safety and assuring consumers of their nutritional properties, microbiological, chemical, and parasitological safety of insects as food is key to marketing these products. In particular, this review addresses a notable gap in the current literature by highlighting the paucity of primary research providing concrete evidence of safety, as most existing studies rely on theoretical assumptions or generalized claims. This review uniquely consolidates data on microbiological and allergenic risks, chemical contamination, and mitigation strategies. Additionally, it emphasizes the pressing need for more specific legislation to regulate insect-based foods, to address current ambiguities and to foster consumer confidence. By combining these perspectives, this review aims to not only provide a roadmap for future research and practical applications but also to serve as a foundation for informed policymaking in this rapidly evolving field.

Food safety concerns

The staggering statistics surrounding foodborne diseases highlight a pressing global health crisis that demands immediate attention (European Food Safety Agency (EFSA) 2024). With over 2 million deaths each year in developing nations and more than 2 billion illnesses linked to just 13 zoonotic diseases, the burden falls disproportionately on vulnerable populations such as the elderly, infants, children, and those with weakened immune systems (Odeyemi et al. 2019). This reality underscores the critical importance of prioritizing public health initiatives aimed at improving food safety and education worldwide. By addressing these issues head-on, we can strive toward a healthier future where the threat of foodborne diseases is significantly reduced, ultimately safeguarding the lives of countless individuals across all demographics (Odeyemi et al. 2019).

The integration of edible insects into global markets faces challenges, particularly due to limited data on microbiological and chemical safety hazards during production and processing (Tchonkouang, Onyeaka, and Nkoutchou 2024). Despite these obstacles, the rearing, processing, and use of edible insects have garnered substantial scientific interest driven by growing consumer demand. The following Figure 1 presents key milestones in entomophagy over the past decade, focusing on research related to human consumption for the five most popular edible insect species: *Tenebrio molitor*, *Acheta domesticus*, *Bombyx mori*, *Locusta migratoria*, and *Alphitobius diaperinus*. Therefore, from a food safety perspective, there remains a significant knowledge gap, with limited studies on the role of edible insects in food safety, as illustrated in Figure 1.

Since 2014, a total of 622 research articles, regarding the aforementioned species, were published, comprising 91.9% of the 677 total publications on the topic. This was followed by review articles (49), representing 7.2%, and other documents, including editorial materials like book chapters, accounting for 0.9%. The number of studies in this area has been growing substantially since then, with *T. molitor* emerging as the most studied species with 316 publications (46.7% of the total), confirming its position as the trendiest edible insect in research at the moment. This is followed by *A. domesticus*, with 174 publications (25.7%), and by *B. mori*, *L. migratoria* and *A. diaperinus*, which together account for only 27.6% with 187 publications. However, most of the published research on insects comes from the field of entomology and focuses mainly on agriculture rather than food (Kavle et al. 2022). This highlights the need for a more interdisciplinary approach to the study of insects as a sustainable food source. Although Scopus statistics suggest that this is a very young field of study, as evidenced by the unusually long “lag” period observed between 1977 and 2012, as awareness of the environmental benefits of entomophagy grows, researchers are increasingly encouraged to explore its potential to address global food security and safety challenges.

To ensure the safe integration of insects into the food supply chain, it is crucial to identify and control potential foodborne hazards that may arise during the processing, distribution, and consumption of these insects. Since edible

insects are often produced in environments distinct from conventional livestock, food safety measures must be tailored to the unique characteristics of insect farming. This includes assessing contamination risks associated with rearing conditions, feed quality, and post-harvest practices.

The implementation of Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP), combined with multidisciplinary collaboration between food safety teams and product development departments, provides a structured approach to identifying, analyzing, and controlling physical, chemical, and biological hazards. Such efforts are essential to prevent contaminants from entering the food supply chain and to ensure that edible insects meet the necessary safety standards for human consumption (Arévalo et al. 2022; Wallace, Sperber, and Mortimore 2011). This collaboration not only enhances food safety but also fosters innovation in developing safer processing techniques and formulations.

Figure 2 highlights the stages within the *T. molitor* supply chain that requires consideration for the implementation of GMP and HACCP principles. These interventions aim to ensure food safety at every stage of production. For a more detailed exploration of HACCP system implementation in *T. molitor* larvae meal production, we recommend consulting the review by Arévalo et al. (2022).

Hazard (biological, chemical and physical) analysis is the first of the seven principles of a HACCP plan. These assessments not only guide the identification of potential food safety hazards but also play a vital role in ensuring compliance with regulatory frameworks (U.S Food and Drug Administration (FDA) 2022). Given the importance of aligning hazard management practices with legislative requirements, the following subsections explore the existing legislation governing edible insects as food products, as well as the identification of potential food safety hazards associated with their production and consumption.

Legislation

The development of novel foods is not only about satisfying hunger and providing essential nutrients but also about preventing diet-related and foodborne illnesses (Knezevic et al. 2021); thus, the legislation sets the framework and standards that guide the identification of potential food safety hazards and management of these hazards.

Regulation (EU) No 2015/2283, legislation regarding the introduction of novel food products, regulates the production and marketing of food products in the European Union. It defines novel foods as those that “were not used for human consumption to a significant degree” within the European Union prior to the 15th of May 1997, which includes insects (Fuso et al. 2024).

Since no specific regulation regarding the production and consumption of insects exists, edible insects must also follow the same legal path as other foodstuffs, such as the “General Food Law”, Regulation (EC) No 178/2002, and the “Official Controls Regulation”, Regulation (EU) 2017/625. Regulation (EC) No 258/97 posed legal uncertainty regarding the

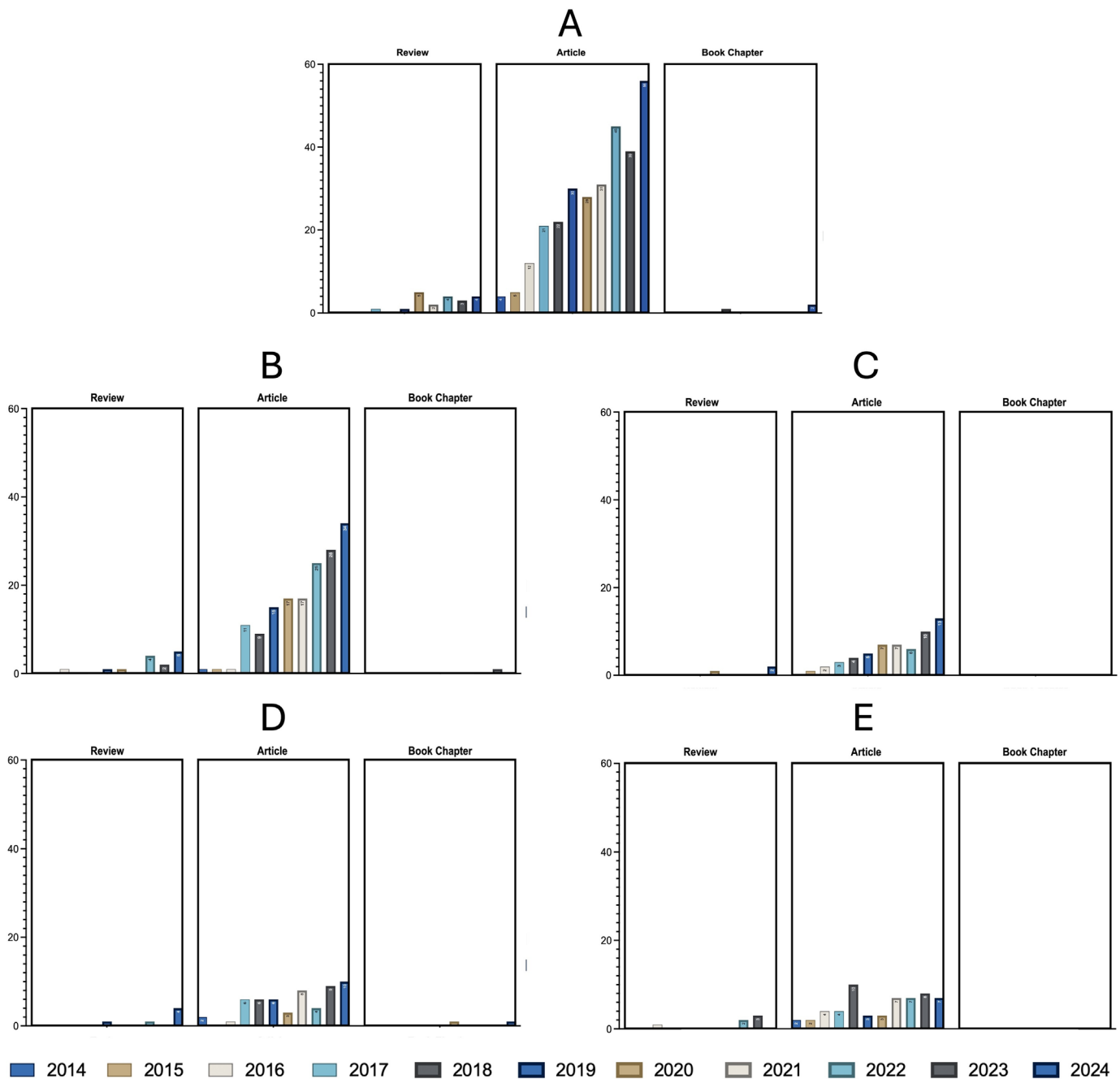


Figure 1. Number of studies published annually and available in the Scopus database on the topic of the five most popular edible insect species, illustrating the trend in academic interest over time. A—*Tenebrio molitor*, B—*Acheta domesticus*, C—*Bombyx mori*, D—*Locusta migratoria* and E—*Alphitobius diaperinus*.

classification of entire insects as new foods, resulting in differing responses across EU Member States and a contrasting influence on transitory measures under Regulation (EU) 2015/2283 with Belgium, Finland, the Netherlands, Denmark, Norway, Switzerland, Germany and Portugal applying the transitional measures. These countries have, therefore authorized the production and marketing within their jurisdictions although maintaining some import restrictions (International Platform of Insects for Food and Feed (IPIFF) 2021). Nonetheless, in the European Union, four species have been approved for human consumption (*T. molitor*, *L. migratoria*, *A. domesticus* and *A. diaperinus*). In the United Kingdom, since Brexit, the Food Standards Agency has

declared the end of transitional measures as of 1st of January 2024, and the only species allowed to be marketed without special authorization are those that meet the original European Union's conditions and those subject to current application under the United Kingdom's and Scotland's Novel Foods Regulation by 31st of December 2023 (Food Standards Agency (FSA) 2024). Valid novel food applications have been submitted for four insect species (*T. molitor*, *A. domesticus*, *Grylloblatta campodeiformis* and *Hermetia illucens*) (Commission Implementing Regulation (EU) 2021, 2022, 2023a, 2023b).

In the United States of America, the Food and Drug Administration regulates edible insect production for human consumption under the Federal Food, Drug and

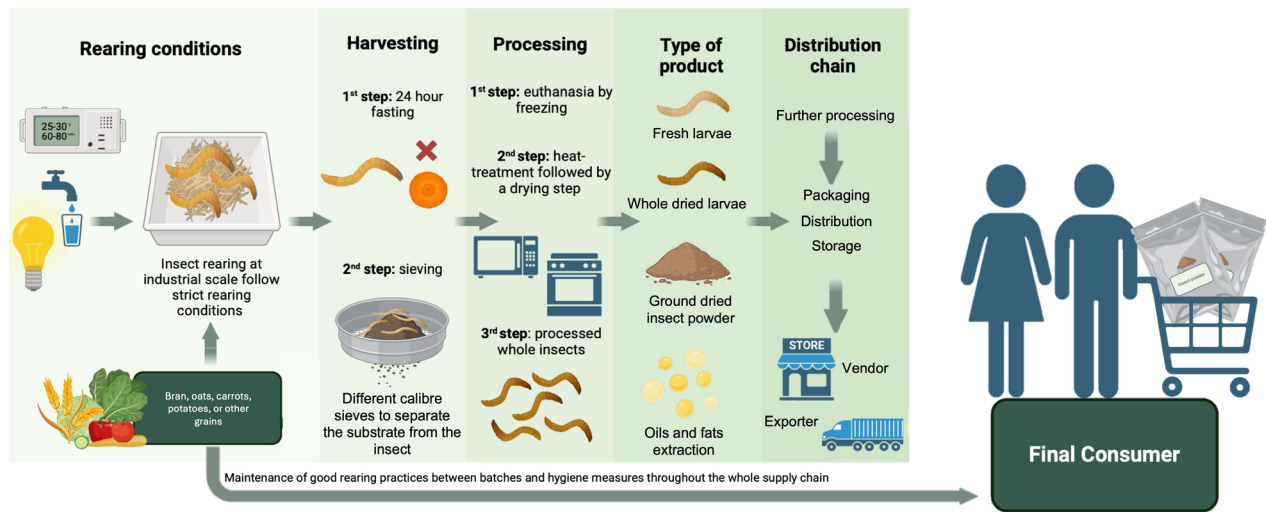


Figure 2. Illustration of the various stages of the *Tenebrio molitor* production process, from initial cultivation to distribution for consumption.

Cosmetic Act. Since certain insect species have been Generally Recognized as Safe (GRAS), insects may be considered food, or food additives, if regulatory requirements imposed on other foodstuffs are met and if reared to be consumed by humans (Larouche et al. 2023). Insect rearing for human consumption must follow the current Good Manufacturing Practice in Manufacturing, Packing or Holding Human Food (21 CFR 110 (CFR 2024a)). Crickets, mealworms, some honeybee species, and similar insects that are routinely farm-raised are included in Importation, Exportation and Transportation of Wildlife under Regulation 50 CFR 14 (CFR 2024b), in which import/export licenses and inspection fees for wildlife in the form of food for commercial purposes are applied (CFR 2024b). Some species have been added to the authorized importation list of foods, Import Prior Notice (U.S Food and Drug Administration (FDA) 2023).

In Canada, edible insects may be sold without regulatory limitations if a documented history of safe consumption is available. However, with the exception of three species (*T. molitor*, *Alphitobius diaperinus* and *G. sigillatus*), already regarded as non-novel foods, their production and marketing being thus allowed, other species are still be considered a novel food, requiring, therefore, the compliance of the Guidelines for the Safety Assessment of Novel Foods (Health Canada 2022; Larouche et al. 2023). Edible insects in Canada must adhere to the same safety standards as other food products sold online or in stores. Manufacturers must comply with the SFCR when imported, exported, or sold interprovincially. To guarantee food safety, the Canadian Food Inspection Agency (CFIA) and Health Canada monitor hazards in edible insects, adhering to specific food safety and nutritional quality policies, ensuring that edible insects meet the same rigorous safety criteria as traditional food items, protecting consumers from potential health risks. By enforcing these regulations, authorities aim to foster confidence in the growing market for edible insects (Canadian Food Inspection Agency (CFIA) 2021).

In Australia and New Zealand, novel foods and novel food ingredients are regulated by the Food Standards Code (1.1.1 and 1.5.1, respectively). Three insect species (*Zophobas morio*, *A. domestica* and *T. molitor*) have been approved for human consumption, but they are regarded as not novel (Department of Agriculture and Fisheries and Forestry (DAFF) 2024b). When importing insects for human food or animal feed, they must be dead and heat-treated. The Department of Agriculture, Fisheries and Forestry regulates food imports into Australia and reviews each application on an individual basis. For each planned live insect species, entomophagy farmers must seek formal clearance from the competent Primary Industries and Biosecurity authority in their state or territory. This is subject to rules under the Biosecurity Act of 2015. Before growing or processing insects, a species list (containing common and scientific names) must be submitted for approval (Department of Agriculture and Fisheries and Forestry (DAFF) 2024a).

Even though African and Asian countries have a rich history regarding entomophagy, no legislation is in force (Grabowski et al. 2022; Lähteenmäki-Uutela, Marimuthu, and Meijer 2021). The Korean Food and Drug Administration considered some insect species as normal food without further restriction (Han et al. 2017). In China, even though no regulatory legislation is in place, insects are a common commodity, with only mentions of mealworms and silkworms being found in food safety catalogues (Xie et al. 2024). On the other hand, Japan has acknowledged several insect species as traditional foods (grasshoppers, wasps, moths and silkworms), with novel foods not needing pre-market authorization (Lähteenmäki-Uutela, Marimuthu, and Meijer 2021). Alternatively, the Singapore Food Agency has set guidelines for insect import, farming, and processing, including assessing insect species for human consumption history, preventing the introduction of contaminants, and ensuring safe product quality. These guidelines are based on scientific reviews from regions and countries such as the European Union, Australia, New Zealand, South Korea, and Thailand. The general consumption of foods consisting of or

containing ingredients from a list of 16 insect species has been approved for human consumption (Singapore Food Agency (SFA) 2024).

A summary of the legislation status of edible insects around the globe can be found in Table 1.

As reported by the Organisation for Economic Co-operation and Development (OECD) (2010), trade regulations, including import restrictions, can significantly impact market dynamics. Import regulations, in particular, may influence the growth of the edible insect market by creating barriers to entry for producers in exporting countries. These barriers can affect the efficient allocation of resources, disrupt international trade, and limit the competitiveness and development of industries in both exporting and importing countries. Furthermore, such regulations can introduce volatility in the global edible insect market, where producers may hesitate to invest in production capacity due to uncertain market access. In addition to these trade challenges, the approval process for edible insect species varies significantly between regions, further complicating their global market expansion (Veldkamp et al. 2022). This disparity in approval standards due to distinct regulatory approaches, not only delays the global integration of insect-based products but also restricts the variety of species available in international markets. These challenges underscore the importance of harmonizing regulations across countries to facilitate the growth of the edible insect industry and support its integration into global food systems.

The ever-changing regulatory landscape, the continuous efforts to expand the edible insect industry and market, and the incessant search for sustainable production can have a negative impact on the legitimacy and traceability of this type of product along the production chain (Fuso et al. 2024). The development of regulatory frameworks and the adaptation of legislation for insect-based foods, as well as the consumer acceptance of entomophagy, still require a great deal of work and the resolution of several challenges. In order to support self-regulation and the growth of this industry, it is essential to promote standards for insects used for human consumption at both national and international levels based on data-driven safety assessments through the proactive collaboration of academics, businesses and policymakers.

Risk profile: biological hazards in edible insects

Microbiological risk

When assessing the microbiological characteristics of edible insects, it is important to acknowledge that insects are naturally occurring carriers of microorganisms. It is necessary to determine if microorganisms are mechanically transferred by touching the insect's body or if they can live and grow inside the insect without causing illness to the host. This distinction is crucial because it impacts the risk assessment and mitigation strategies for food safety (Gałęcki, Bakuła, and Gołaszewski 2023).

Pathogenic microorganisms, including viruses, bacteria, protozoa, fungi, nematodes, and other parasites of the

human digestive tract can be spread by insects (Schlüter et al. 2017). While autochthonous microbiota will be influenced by species, developmental stage, allochthonous microbiota will be influenced by rearing conditions, feeding, processing, handling, and storage (Garofalo et al. 2019). Therefore, knowing the full scope of interactions that may lead to the presence of foodborne pathogens is imperative for the assurance of product safety (Garofalo et al. 2019; Gałęcki, Bakuła, and Gołaszewski 2023).

Since insects present optimal intrinsic properties (near-neutral pH and high-water activity values) for the growth of several microorganisms, high microbial loads are expected in fresh insects (Aleksavičius et al. 2022; Fernandez-Cassi et al. 2020; Nyangena et al. 2020; Okaiyeto et al. 2024; Vandeweyer et al. 2017). Table 2 summarizes the most commonly found bacteria in edible insects, being these, *Bacillus* spp., *Campylobacter* spp., *Staphylococcus* spp., *Streptococcus* spp., *Pseudomonas* spp., *Acinetobacter* spp., *Micrococcus* spp., *Lactobacillus* spp., *Clostridium* spp., *Klebsiella* spp., and *Serratia* spp. (Garofalo et al. 2019; Inácio et al. 2021; Schlüter et al. 2017; Vandeweyer et al. 2017).

As shown in Stoops et al. (2016), where the assessment of the microbial quality of fresh yellow mealworms and grasshoppers available in the Belgian market was performed, high numbers of total viable counts, *Enterobacteriaceae* and lactic acid bacteria, between 7- and 9-log, and approximately 3-log of bacterial spores were observed. Additionally, substantial concentrations of yeasts and molds were also perceived. Although these values were obtained for fresh insects without heat processing or further microbiological control hurdles, such as heating, pressure, irradiation, they also highlight several critical points regarding the safety and quality of fresh insects as a food source (Stoops et al. 2016). In the study by Inácio et al. (2021) on the impact of starvation on the microbial load of crickets, similarly high levels of total viable counts and *Enterobacteriaceae* were found. The effect of starvation on the microbial load was investigated, revealing results contrary to the expected outcome, with higher bacterial loads observed in insects subjected to longer starvation periods (Inácio et al. 2021).

The *Bacillus cereus* group was considered the top food safety hazard presented by edible insects for human consumption by Vandeweyer et al. (2021) for fresh insects and by Fasolato et al. (2018) for shelf-stable products, asserting the importance of monitoring these spore-forming bacteria (Fasolato et al. 2018; Vandeweyer et al. 2021). The presence of *B. cereus* in both fresh and processed insect products is a key concern, emphasizing the need for stringent monitoring during processing (Vandeweyer et al. 2021).

Taking everything into account, Vandeweyer et al. (2017) have reported three important assumptions regarding the variability of results obtained in studies with edible insects: (i) microbial loads and intrinsic factors vary between rearing companies since different practices and feeds will lead to different outcomes; (ii) results for different insect species must be distinguished as taxonomical dissimilarities will impact nutritional and microbiological safety and quality and (iii) different batches from the same company under the same rearing protocol will lead to differences in insect

Table 1. Overview of the legislative status of edible insects across different regions of the globe.

Region	Authorized species	Production and marketing authorization	Import/Export conditions	Controlling agency	Current legislation	References
European Union	<i>T. molitor</i> ; <i>L. migratoria</i> ; <i>A. domesticus</i> ; <i>A. diaperinus</i>	Yes	Import permissions into the EU market as food are defined by The Novel Food Regulation	EFSA	Regulation (EU) No 2015/2283	Commission Implementing Regulation (EU) 2021, 2022, 2023a, 2023b; Regulation (EU) No 2015/2283; International Platform of Insects for Food and Feed (IPIFF) 2021
United Kingdom	<i>T. molitor</i> ; <i>A. domesticus</i> ; <i>G. sigillatus</i> ; <i>H. illuscens</i>	Yes	Import permissions into the EU market as food are defined by The Novel Food Regulation	Food Standards Agency	Regulation (EU) No 2015/2283	Food Standards Agency (FSA) 2024
United States of America	<i>T. molitor</i> ; <i>A. domesticus</i> ; <i>H. illuscens</i>	Yes	Import/export licenses and inspection fees	Food and Drugs Administration	21 CFR 110 (CFR 2024a)	U.S Food and Drug Administration (FDA) 2023
Canada	<i>T. molitor</i> ; <i>A. diaperinus</i> ; <i>G. sigillatus</i>	Yes, if history of safe consumption	Licensing, preventive controls and traceability requirements under the Safe Food for Canadians Regulations	Canadian Food Inspection Agency	SOR/2018-108	Canadian Food Inspection Agency (CFIA) 2021
Australia	<i>Z. morio</i> ; <i>A. domesticus</i> ; <i>T. molitor</i>	Yes	Regulated by The Department of Agriculture, Fisheries and Forestry; importation allowed if insects are dead, and heat treated	Food Standards Code	Standard 1.1.1 Standard 1.5.1 Biosecurity Act of 2015	Department of Agriculture and Fisheries and Forestry (DAFF) 2024
Africa	Several species are commonly consumed	Yes	ND	Different for every country	Local rules for each country	Lähteenmäki-Uutela, Marimuthu, and Meijer 2021; Smith and Pryor 2013
South Korea	<i>Oxya chinensis sinuosa</i> ; <i>Bombyx batryticatus</i> ; <i>B. mori</i> ; <i>T. molitor</i> ; <i>Gryllus bimaculatus</i> ; <i>Protaetia brevitarsis</i> ; <i>Allomyrina dichotoma</i> ; <i>Zophobas atratus</i> ; <i>Apis mellifera</i> ; <i>L. migratoria</i>	Yes	ND	Korean Food and Drug Administration	Insect Industry Promotion and Support Act	Han et al. 2017; Winconsin Economic Development (WEDC) 2021; Food and Agriculture Organization of the United Nations (FAO) 2019
China	Several species are commonly consumed, however legislation only mention <i>A. domesticus</i> ; <i>B. mori</i> and <i>Lumbricina</i>	Yes	ND	China National Center for Food Safety Risk Assessment	Three New Food catalog	Chemical Inspection and Regulation Service (CIRS) 2022; Lin et al. 2023; Smith and Pryor 2013
Singapore	<i>A. domesticus</i> ; <i>G. sigillatus</i> ; <i>Teleogryllus mitratus</i> ; <i>G. bimaculatus</i> ; <i>Schistocerca americana</i> ; <i>Oxya japonica</i> ; <i>Z. morio</i> ; <i>T. molitor</i> ; <i>A. diaperinus</i> ; <i>P. brevitarsis</i> ; <i>A. dichotoma</i> ; <i>Galleria mellonella</i> ; <i>Achroia grisella</i> ; <i>B. mori</i> ; <i>A. mellifera</i>	Yes	Importation of food for commercial sale in Singapore must comply with the prevailing import requirements	Singapore Food Agency	Regulation of insect and insect products	Singapore Food Agency (SFA) 2024
Japan	Several species are commonly consumed	Normal novel foods do not require pre-market authorization	ND	Ministry of Health, Safety and Welfare	ND	Lähteenmäki-Uutela, Marimuthu, and Meijer 2021

Table 2. Microorganisms found in various edible insect species.

Species	Developmental stage	Associated microorganisms	Sample preparation	Wild/reared	References
<i>T. molitor</i>	Larvae	<i>Enterobacter</i> spp.; <i>Erwinia</i> spp.; <i>Enterococcus</i> spp.; <i>Lactococcus</i> spp.; <i>Spiroplasma</i> spp.; <i>Staphylococcus</i> spp., <i>Clostridium</i> spp., <i>Bacillus</i> spp.	Fresh	Reared	Garofalo et al. 2019; Megido et al. 2017
<i>A. domesticus</i>	Imago	<i>Staphylococcus</i> spp.; <i>Bacillus</i> spp.; <i>Enterococcus</i> spp.; <i>Akkermansia</i> spp.; <i>Acinetobacter</i> spp.; <i>Coprococcus</i> spp.	Fresh	Reared	Aleknavičius et al. 2022
<i>B. mori</i>	Larvae	<i>Odoribacter</i> spp.; <i>Prevotella</i> spp.; <i>Oscillospira</i> spp.; <i>Lactobacillus</i> spp.; <i>Klebsiella</i> spp.; <i>Helicobacter</i> spp.; <i>Methanobacterium</i> spp.	Fresh	Reared	(Shahila Ismail et al., 2023)
<i>L. migratoria</i>	Fifth instar larvae	<i>Weissella</i> spp.; <i>Lactococcus</i> spp.; <i>Yersinia/Rahnella</i> spp.; <i>Enterococcus</i> spp.; <i>Enterobacteria</i> spp.; <i>Pseudomonas</i> spp.	Fresh	Reared	Stoops et al. 2016
<i>Z. morio</i>	Larvae	<i>Citrobacter</i> spp.; <i>Enterococcus</i> spp.; <i>Lactococcus</i> spp.; <i>Pediococcus</i> spp.; <i>Lactobacillus</i> spp.; <i>Weissella</i> spp.	Fresh	Reared	Octavia, 2023
<i>H. illucens</i>	Larvae	<i>Actinomyces</i> spp.; <i>Dysgonomonas</i> spp.; <i>Enterococcus</i> spp.	Fresh	Reared	Klammsteiner, 2020
<i>A. melifera</i>	Pupae	<i>Gilliamella</i> spp.; <i>Snodgrassella</i> spp.; <i>Lactobacillus</i> spp.; <i>Bifidobacterium</i> spp.; <i>Frischella</i> spp.; <i>Commensalibacter</i> spp.; <i>Bombella</i> spp.; <i>Apibacter</i> spp.; <i>Bartonella</i> spp.	Fresh	Reared	Dong et al., 2022 Nowak et al., 2021
<i>A. diaperinus</i>	Larvae	<i>Stenotrophomonas</i> spp.; <i>Pseudomonas</i> spp.; <i>Acinetobacter</i> spp.; <i>Morganella</i> spp.	Fresh	Reared	Cucini et al., 2022
<i>G. sigillatus</i>	Adult	<i>Porphyomonadaceae</i> spp.; <i>Ruminococcaceae</i> spp.; <i>Enterobacteriaceae</i> spp.; <i>Pseudomonadaceae</i> spp.; <i>Bacteroides</i> spp.; <i>Fusobacterium</i> spp.; <i>Parabacteroides</i> spp.; <i>Acinetobacter</i> spp.; <i>Erwinia</i> spp.; <i>Bacillus</i> spp.; <i>Enterococcus</i> spp.	Fresh	Reared	Vandeweyer et al. 2017

characteristics and microbial load. Confirming that rearing conditions (temperature, humidity, substrate) and feed (higher or lower moisture content, microbiological quality) will influence insect growth and quality. Also, the microbiological quality of the substrate will affect the microbiota of the insect, with artificial contamination tests showing that pathogen transfer to the insect can occur and may not compromise physical integrity but may pose a risk when the animal is used as food or feed (Vandeweyer et al. 2021).

Besides bacterial contamination, mycotoxin-producing fungi species may also pose a threat to insect products. These toxic compounds, produced by various filamentous fungi, are commonly found in agricultural products, including grains, fruits, and animal products. Stable and with low molecular weight, mycotoxins can cause severe health issues such as genotoxicity, hepatotoxicity, and neurotoxicity in humans and animals (Bisconsin-Junior et al. 2023; Luo et al. 2021). Regarding insect rearing, the main contamination points lie in the substrate used during rearing, processing and storage (Bisconsin-Junior et al. 2023). Several

mycotoxigenic species have been isolated from insects, namely, *Aspergillus*, *Penicillium*, *Mucor*, *Alternaria*, among others, with isolation of these organisms depending on the insect species and rearing conditions (Garofalo et al. 2019). While research into molds and yeasts present in edible insects, and their impact on food safety is still scarce, with further studies being necessary to discern the implied risks that may follow, prevention and mitigation strategies, such as hygiene protocols and periodic analysis for quality control, are already known to alleviate the risk of contamination and should be implemented (Bisconsin-Junior et al. 2023).

Zoonotic disease risk

Although the industrialization of animal production and climate change may have significantly contributed to the increase in zoonotic infections (Food and Agriculture Organization of the United Nations (FAO) 2013), the risk of zoonotic diseases from entomophagy is believed to be minimal due to the significant taxonomic separation between humans and insects. Most entomopathogens are not involved

in zoonosis epidemiology and do not pose a threat to humans (Doi, Gałęcki, and Mulia 2021). Even more, insect farming can reduce the prevalence and spread of zoonotic diseases by eliminating pathogen carriers from the food chain (Gałęcki, Bakula, and Golaszewski 2023).

According to EFSA, the consumption of edible insects is safe under certain conditions, such as insect sourcing from controlled environments and species-specific assessments (European Food Safety Agency (EFSA) 2015). Edible insects are highly unlikely to act as disease vectors, as they are fed agri-food by-products and plant-based products, reducing the risk of transmission of zoonotic pathogens. However, *Bacillus popilliae* has been reported to be infectious to a few selected species in the order Coleoptera, and *Bacillus thuringiensis* has been reported to a broader host spectrum within the order Lepidoptera and can infect many species (Maciel-Vergara et al. 2021). A 2010 study by Noonin et al. (2010) has shown that *Aeromonas hydrophila* is pathogenic toward yellow mealworm larvae, asserting the importance of studying how entomopathogens may impact insect health and safety. To minimize risk, insect farms should follow biosecurity standards, including disinfecting work surfaces, maintaining personal hygiene, regularly cleaning premises, and observing safe food preparation and delivery practices (Gałęcki, Bakula, and Golaszewski 2023). Practicing these measures not only protects the health of the consumers but also enhances the overall quality and sustainability of the insect farming industry (Baigts-Allende and Stathopoulos 2023).

Risk profile: chemical contaminants

Similar to animal products, hazardous chemicals may be present in edible insects and can accumulate throughout the food chain. The prevalence of chemical pollutants in insect products depends on several factors, including production techniques, substrate, harvest stage, and insect species, as different species exhibit varying bioaccumulation potential (European Food Safety Agency (EFSA) 2015).

In the last decade, several reports on the presence of harmful chemicals have been published, bringing insight to the chemical safety of these products (Kolakowski et al. 2021; Macan Schönleben et al. 2024; Meyer et al. 2021; Murefu et al. 2019; Papastavropoulou, Xiao, and Proestos 2023; Poma et al. 2017; Poma et al. 2019; Poma et al. 2021; European Food Safety Agency (EFSA) 2015; Van Huis 2015). Poma et al. (2017) evaluated the chemical content of four insect species and four insect-based products, providing an in-depth account of residual levels of various compounds, as shown in Table 3.

The results showed that, even though several chemicals can accumulate in insects, the levels found were comparable to or lower than those found in animal products, supporting the viability of insects as a food source (Poma et al. 2017). The incidence of common chlorinated pollutants, along with emerging contaminants such as PCBs, polyhydroxyalkanoates (PAHs), brominated flame retardants (BFRs), phosphorus flame retardants (PFRs)), has been examined in edible insects (Liu, Li, and Gómez 2019; Poma et al. 2017, 2021).

Poma et al. (2021) suggested that persistent organic pollutants (POPs) were likely accumulated by insects during rearing or from the wild environment, while phosphorus flame retardants (PFRs) and plasticizers originated from post-harvest industrial handling and seasoning, with pollution patterns differing and no correlation between contaminant levels in insects and food packaging, indicating that food contact materials are not a major source of contamination. In the study of Liu, Li, and Gómez (2019), the authors found that PFRs and plasticizers accumulated differently across insect species and developmental stages, with ecdysis acting as a key mechanism for eliminating contaminants, highlighting the complex bioaccumulation dynamics influenced by factors such as habitat, feeding habits, and the physicochemical properties of the chemicals.

Meyer et al. (2021) presented an overview of potential chemical hazards in reared insects, noting that the bioaccumulation of heavy metals depends on the type of heavy metal, species, and substrate. It was highlighted that dioxins and dioxin-like PCBs, despite being globally banned due to their toxic effect, may still contaminate insects due to their presence in soils, air, and sediment (Meyer et al. 2021). However, concentrations found have consistently been below the maximum allowed levels for food and feed set by the European Union (Commission Implementing Regulation (EU) 2023/915 (Commission Implementing Regulation (EU) 2023c). Notably, higher concentrations of these compounds were observed in edible compared to processed insect products, probably due to dilution within a more complex matrix (Meyer et al. 2021; Poma et al. 2017).

In the case of mycotoxins, no evidence of mycotoxin accumulation in insect tissue has been found (Bisconsin-Junior et al. 2023). Fasting practices and the replacement of contaminated substrates have been proven to be enough to achieve a decrease in mycotoxin concentration, keeping levels below the maximum residue limits of mycotoxin in food (Bisconsin-Junior et al. 2023).

Contamination with chemicals may be deterred if proper rearing conditions are ascertained, from substrate and feeding to post-harvest handling. Even though more studies are

Table 3. Concentration ranges of hazardous chemicals in edible insects and insect-based foods (Poma et al. 2017).

Chemical group	Compounds analyzed	Concentration range (pg/g wet weight)
Polychlorinated Biphenyls (PCBs)	Sum of 7 indicator PCBs (PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, PCB-153, PCB-180)	26.5–2065
Organochlorine Pesticides (OCPs)	DDT and its metabolites (p,p'-DDT, p,p'-DDE, p,p'-DDD)	46.3–368
Brominated Flame Retardants (BFRs)	Polybrominated diphenyl ethers (PBDEs) and other BFRs (BDE-47, BDE-99)	Up to 35.5
Phosphorus Flame Retardants (PFRs)	Various PFRs (triphenyl phosphate, tris(2-chloroethyl) phosphate)	783–23,786
Dioxin Compounds	Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs)	Up to 0.25 pg WHO-TEQ/g wet weight

necessary to come to confident conclusions, evidence suggests that, chemically, edible insects do not pose a liability bigger than meat products. However, the complexities surrounding emerging chemical risks in the food chain highlight the urgent need for vigilance and proactive measures. Both intentional and unintentional contamination, whether stemming from anthropogenic activities or natural sources, pose significant challenges to public health and environmental safety, as described in the following section.

Emerging chemical contaminants

Agrochemicals. Pesticides play an essential role in present-day agriculture, improving crop productivity and quality. Misuse of pesticides can endanger human and environmental safety, cause pest revival, secondary outbreaks, pest resistance, and loss of biodiversity. Regarding edible insects, the presence of such chemical contaminants is probable since it may be present in feed, commonly vegetables, as well as rearing substrate, usually wheat bran or cereal-derived products (Morales-Ramos et al. 2024). Because of their hazardous, persistent, and bioaccumulative characteristics, pollutants such as organochloride pesticides are nevertheless widely found in the environment and in people, even with usage limitations in place (Poma et al. 2021). The risk that pesticides may pose for the chemical safety of edible insects relies on numerous factors but, most importantly, on the rearing process and feed quality. For laboratory- or industrially reared insects, there is a lower risk associated with the bioaccumulation of pesticides along the food chain, as reported by Van Der Fels-Klerx et al. (2018) and Meyer et al. (2021), while for wild-caught edible insects, the risk of contamination is higher (Labu et al. 2022). The valorization (utilization) of agricultural waste as insect feed poses a risk of pesticide accumulation in the insects. Pesticides used in agriculture may linger in foodstuff and accumulate during the insect's life cycle (Houbraken et al. 2016; Macan Schönleben et al. 2024). However, studies by Poma et al. (2021) demonstrated that the precise sources of contamination of edible insects are difficult to identify since many factors are involved, from the insect species to the production chain processes. It was concluded that the assessment of chemical hazards should not only focus on the transfer and accumulation of compounds by the insects during rearing but also on the possible post-harvest contamination of the product (Poma et al. 2021). Houbraken et al. (2016) reported that even though pesticides are readily accumulated in insects, fasting may help lower levels of contamination. Nonetheless, the uptake and excretion by the arthropod varies according to the characteristics of the pesticide (Houbraken et al. 2016).

To assess the potential risks to food and animal safety, Meijer et al. (2021) investigated the effect of various insecticides on growth, survival, and bioaccumulation in black soldier fly

larvae (*H. illucens*) concluding that, although no accumulation of insecticides at worrying levels has been observed in BSFL larvae, insecticides can have significant effects on the health and growth of larvae and should, therefore, be considered in rearing management and safety regulations. Similarly, Labu et al. (2022) analyzed six species of wild-caught edible insects from Uganda and Kenya to determine the presence of agrochemical residues, comparing them with the maximum residue limits (MRLs) established by the Codex Alimentarius Commission. Nine agrochemicals were detected in edible insects; of these, two insecticides were observed (aminocarb and pymetrozine), emphasizing the need for monitoring and regulation to ensure the safety of edible insects, as they can accumulate insecticide residues from the environment.

Pharmaceuticals. Since the chemical quality and safety of insects are heavily influenced by their feed, by feeding on agricultural co-products, by-products, and waste streams that are not yet valorized, several insect species may accumulate pharmaceutical drugs, most likely from veterinary use (De Paepe et al. 2019). When analyzing real insect samples, De Paepe et al. (2019) have found that some veterinary drugs were detected, such as salicylic acid, metoprolol and paracetamol. Salicylic acid was detected in all the samples, which may be due to its use in animals and its presence in fruits and vegetables. Paracetamol was also found in some samples and is a common analgesic that easily accumulates in the aquatic environment. Metoprolol tartrate, used to treat cardiovascular diseases, was also detected above the screening detection limit SDL in some samples. This paper does not establish maximum residue limits (MRLs) for veterinary drugs in insects but compares the SDLs obtained with the MRLs established for other edible matrices. Meyer et al. (2021) have reported that scarce studies are available on the topic, and four years later, the same is still verified, calling for more research into these emerging contaminants that may threaten the food safety of edible insects.

Antibiotic resistance genes. As brought to light by EFSA, antimicrobial resistance genes (ARGs) must be taken into consideration when assessing the risk profile of insects used as food (European Food Safety Agency (EFSA) 2015). The use of antibiotics in several industries, including human health, agriculture, and veterinary medicine, contributes to the natural and widespread occurrence of antimicrobial resistance. Owing to these considerations, some studies have been taken to assess the presence of antibiotic-resistance genes in edible insects found on the market. Milanović et al. (2018) examined the presence of transferable antibiotic resistance genes (ARGs) in commercially available edible insects to establish a baseline for risk assessment. The study screened eleven specific ARGs in several insect species and found that the most common genes were *tet(K)*, *erm(B)*, *tet(S)*, and *blaZ*, while

four genes (*erm(A)*, *vanA*, *vanB*, and *mecA*) were absent. Vandeweyer et al. (2019) assessed the presence of antibiotic resistance (AR) genes in fresh edible insects, namely mealworms and crickets, from different rearing facilities in Belgium and the Netherlands. The results showed that insects could contain considerable amounts of antibiotic resistance genes, comparable to other food matrices and that their occurrence varies between insect species and geography. The research suggests that insects may be a vehicle for transferring AR genes to the human digestive tract. Raka et al. (2024) compared the presence of ARGs in edible insects to revealing edible insects exhibited a higher prevalence of tetracycline resistance genes (*tet*), whereas cattle showed a greater abundance of both *tet* and erythromycin resistance genes (*erm*), along with several strains of beta-lactamase resistance genes (*bla*). The findings suggest that edible insects could contribute to the dissemination of ARGs, emphasizing the importance of continued surveillance to assess their role in the food chain and the influence of factors like legislation and sanitizers on microbial resistance. Understanding the presence and spread of ARGs in insect rearing is crucial for ensuring their safety as a sustainable protein source. Factors influencing ARG proliferation include farming practices, feed sources, and environmental conditions. Addressing these can help develop guidelines for safe insect farming and minimize antibiotic resistance transmission.

Allergenic risk assessment

Food-induced allergies are becoming a more significant worldwide public health issue. The only effective treatment

for allergy sufferers is completely avoiding allergy-triggering foods. Entomophagy has long been recognized to cause allergic reactions, and studies on this subject have recently gained traction (Belluco et al. 2013; Cunha et al., 2023). This has prompted concerns regarding the potential of edible insects to trigger widespread food allergies, making allergenicity risk assessment (Figure 3) imperative for these novel foods (Garino, Zagon, and Braeuning 2019).

An allergen is an antigen that can stimulate a type 1 hypersensitivity reaction in atopic individuals. In these reactions, the immune system fights off a perceived threat that would otherwise be harmless through IgE responses (Abbas, Moussa and Akel 2023). Allergic reactions caused by eating insects may be classified into two types: primary sensitization to edible insects and cross-reactivity with other allergenic species (de Gier and Verhoeckx 2018).

Primary sensitization

Primary sensitization typically occurs early in infancy. In atopic individuals who have a predisposition toward developing IgE-associated allergies, the production of cytokines induces the production of allergen-specific IgE. This primary contact with the allergen will lead to T-cell and IgE memory that can be boosted by repeated exposure to the allergen (Valenta et al. 2015). Studies in humans have shown that exposure to edible insects can lead to primary sensitization (Broekman et al. 2017; Okezie, Kgomotso, and Letswiti 2010; Pener 2014; Pirokrat, Chinratapisit, and Trathong 2008; Verhoeckx et al. 2016; Zhao et al. 2015). Sensitization may occur via oral, skin contact, and inhalation exposure (Broekman et al. 2017). Prolonged exposure to insects has been proven to be the root of occupational allergies. This has been reported among insect breeders, entomologists, and laboratory personnel, with studies covering a wide range of

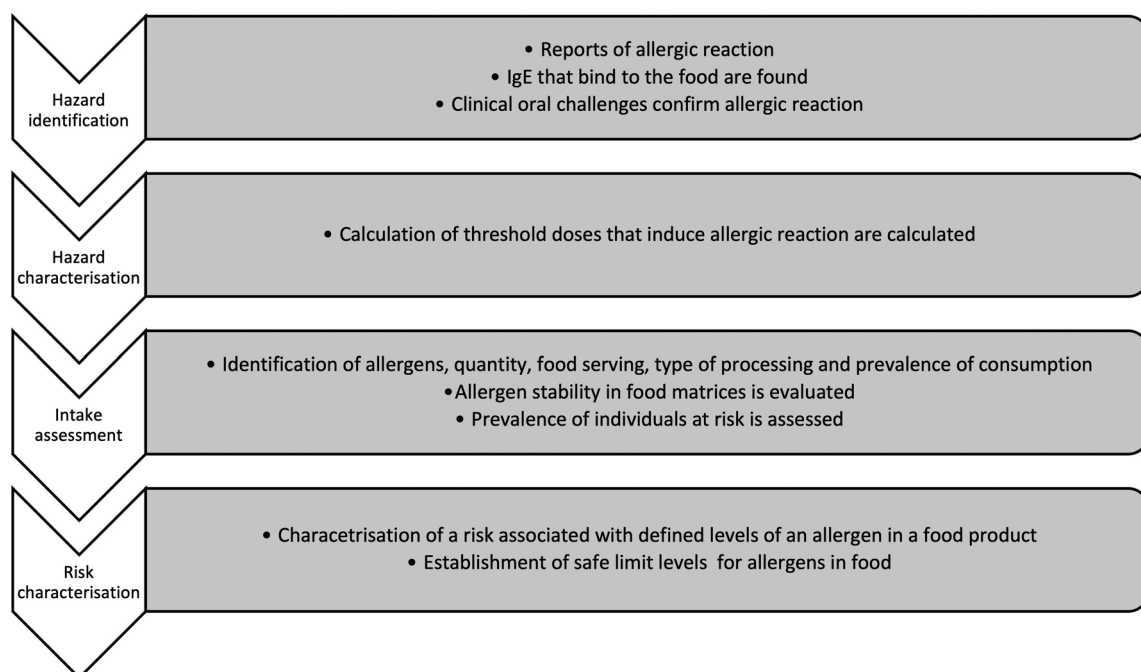


Figure 3. Allergen risk assessment (Garino, Zagon, and Braeuning 2019).

edible insect species (de Gier and Verhoecx 2018; De Marchi, Wangorsch, and Zoccatelli 2021; Ganseman et al. 2023; Lopata et al. 2005; Pener 2014). However, studies on primary sensitization remain limited. Further research is essential to determine whether allergic reactions are caused by species-specific allergens or cross-reaction allergens (de Gier and Verhoecx 2018).

Cross-reactivity

The majority of insect allergens that are IgE-binding allergens also cross-react with allergens found in shellfish, mollusks, and nematodes. These IgE-binding cross-reacting pan-allergens are widely distributed throughout different animal phyla (Barre et al. 2021). Examples of these pan-allergens include tropomyosin, arginine kinase, glyceraldehyde 3-phosphate dehydrogenase, alpha-actin, enolase, fructose-1,6-biphosphate aldolase, alpha-amylase, glutathione S-transferase, myosin, paramyosin, triose-phosphate isomerase and troponin (De Marchi, Wangorsch, and Zoccatelli 2021; Verhoecx et al. 2014). Barre et al. (2021) concluded that the IgE-specific allergens identified in edible insects essentially correspond to pan-allergens, which develop some IgE-binding cross-reactivity with other homologous proteins present in other arthropods (mites, crustaceans), mollusks and nematodes. This paper has established pan-allergens that cause cross-reactivity, including alpha-actin (a common structural protein in many species), arginine kinase (an enzyme involved in energy metabolism), enolase (glycolytic enzyme), fructose-1,6-biphosphate aldolase (glycolysis enzyme); glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (glycolysis enzyme) and tropomyosin (a protein involved in muscle contraction), can trigger allergic reactions in people sensitized to other arthropods, mollusks and nematodes, making it a problem for people with preexisting allergies.

Multiple sensitizations may be a consequence of sensitization to these pan-allergens, which may also be possible for species-specific allergens (Raheem, Raposo, et al. 2019). Since cross-reactivity reflects the phylogenetic relations between organisms, individuals may not discern what allergens induce an allergic reaction. Cross-reactions between allergens from different invertebrates may occur if certain foods are consumed (Aalberse, Akkerdaas, and van Ree 2001; Francis et al. 2020). This cross-reactivity has been reported in crustaceans- and house dust mites- allergic patients exposed to different edible insects, particularly yellow mealworms, and crickets (Broekman et al. 2017; Kamemura et al. 2019; Srinroch et al. 2015; Verhoecx et al. 2014). Broekman et al. (2017) and De Marchi, Wangorsch, and Zoccatelli (2021) have also demonstrated that individuals allergic to crustaceans and house mites are at high risk of an allergic reaction due to the presence of pan-allergens (Broekman et al. 2017; De Marchi, Wangorsch, and Zoccatelli 2021).

Prior sensitization to insects or homologous invertebrates is plausible since most allergic reactions reported occurred right after ingestion of the insect (Ribeiro et al. 2018). These findings emphasize how crucial it is to identify the allergens

causing insect allergic reactions by collecting sera from patients. (De Marchi, Wangorsch, and Zoccatelli 2021; Ribeiro et al. 2022). Additionally, according to Fuso et al. (2024), the allergenicity risk of edible insects may also be linked to food fraud if: (i) edible insects are present in insect-free food formulations (excluding unintentional contamination scenario); (ii) the presence of allergens is not disclosed (including unintentional contamination scenario) and (iii) different insect species are knowingly used instead of what is reported on product description.

Physical threats

Physical hazards can be broadly classified as sharp hazards, choking hazards, and conditions of animal food hazards such as size and hardness (U.S Food and Drug Administration (FDA) 2022). Injuries from physical hazards may include oral cavity damage (e.g., tooth damage or laceration of the mouth or throat), laceration or perforation of the gastrointestinal tract, and choking. In general, there is an overlap between facility-related physical hazards and process-related physical hazards. These can be used in several phases of food production, including harvesting, processing, packaging, and distribution. Physical hazards may often be caused by poor equipment maintenance, insufficient quality control, and inadequate inspection processes throughout the manufacturing process (U.S Food and Drug Administration (FDA) 2024). When present in foods, these hazards represent significant risks to consumers. Regarding edible insects, FAO has reported that risks may lie in whole dried insects' hard components, including wings, stings, and mouthparts, among others, depending on species, that may pose a risk when ingested. All products that contain, or may contain, insect parts must be on the ingredient list (Food and Agriculture Organization of the United Nations (FAO) 2021). To prevent physical food hazards, firms should apply stringent quality control procedures, such as frequent equipment maintenance and rigorous examination of raw ingredients and final products. These measures help ensure that any potential risks are identified and mitigated before the food reaches consumers. By prioritizing safety at every stage of production, businesses can protect public health and maintain consumer trust.

Risk mitigation strategies

Insects have historically been prepared in diverse ways, with methods varying depending on the species, life stage, and cultural traditions. Typically, they are consumed whole or in identifiable forms, roasted, or fried as primary or secondary ingredients. (Hernández-Álvarez et al. 2021; Ros-Baró et al. 2022).

As mentioned in Section “ Microbiological risk,” high microbial loads can be found in fresh edible insects (Stoops et al. 2016). This demands the quest for an appropriate processing procedure to promote customer acceptability and eradicate possible infections in insect-based food components (Liang et al. 2024). As the demand for alternative

protein sources continues to grow, optimizing these processing techniques will be crucial for meeting consumer expectations and maintaining food safety standards (Hernández-Álvarez et al. 2021). Traditional sun-drying, microwave processing, freeze-drying, oven-drying, dry fractionation, freezing, marinating, and fermentation are some of the methods that can be employed (Borremans et al. 2018; Khatun et al. 2021; Kurdi et al. 2021; Nyangena et al. 2020; Ojha et al. 2021; Purschke et al. 2018; Ribeiro et al. 2022; Van Campenhout 2021). Additionally, several insect-based products have been successfully created, including ground beef, biscuits, and chocolates, in order to be more attractive to Western consumers (Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro 2019). Naturally, the sensory and nutritional properties of the goods produced by each method vary.

Blanching is a pretreatment process that reduces microbial counts and inactivates degradative enzymes responsible for food spoilage and poisoning (Ribeiro et al. 2024). It significantly reduces the total counts of mesophilic bacteria, yeasts, and molds but is ineffective in eliminating or reducing mesophilic bacterial spores. Blanching should be specifically designed for each insect species to improve antimicrobial effects with minimal loss of quality (Cacchiarelli et al. 2022; Ribeiro et al. 2024).

Drying, ranging from traditional methods like baking, frying, and sun-drying to modern methods like freeze-drying and microwave-assisted drying, is the most widely used technology to increase food shelf life. Insects can be dried in the sun for at least 2 days to increase their shelf life (Liang et al. 2024; Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro 2019). Solar drying is mainly used in homes due to low energy consumption but can have poor sanitary quality due to contact with soil and air conditions (Yisa et al. 2023). Oven-dried products are comparable but have lower energy input costs, reduced lipid oxidation, and high protein solubility. Microwave drying has been shown to significantly decrease water activity ($a_w < 0.30$), which resulted in a notable drop in microbiological counts (Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro 2019). Innovative technologies, such as freeze-drying, is a costly process that freezes and removes ice, making high-quality edible insects with excellent nutritional value and long shelf life (Hernández-Álvarez et al. 2021). Dry fractionation increases protein-enriched fractions, promising for industrial applications and consumer acceptance, as Purschke et al. (2018) demonstrated in mealworm larvae.

Fermentation has also been used as a strategy for enhancing the shelf life and microbiological safety of edible insects, with research demonstrating that fermentation can reduce the growth of harmful bacteria (Borremans et al. 2018; Klunder et al. 2012). This process not only prolongs the shelf-life of the insects but also improves their nutritional profile by increasing the availability of certain vitamins and minerals. Additionally, fermented insects may have enhanced flavors, making them more appealing to consumers (Kewuyemi et al., 2020).

As seen, conventional techniques such as solar drying may pose potential health risks due to inadequate hygienic control measures (Melgar-Lalanne, Hernández-Álvarez, and

Salinas-Castro 2019), while contemporary methodologies, including optimized bleaching, heat treatments, and cold atmospheric plasma, have been shown to be more efficacious in reducing microbial contamination, although being more complex and expensive (Bußler et al. 2016; Klunder et al. 2012; Lee et al. 2023).

Regarding nutritional and sensory attributes, novel techniques (e.g., freeze-drying, microwave assisted-drying, cold atmospheric plasma) have been shown to maintain product integrity and properties, while traditional techniques (e.g., sun-drying, blanching, frying) may promote the modification of insect-derived product measures (Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro 2019). Combining traditional methods and new technologies is crucial to optimizing the safety, quality and efficiency of edible insect processing. While traditional methods are rooted in cultural knowledge and local practices, new technologies offer solutions to challenges such as microbial contamination, lipid oxidation and production efficiency. The choice of processing method must consider the type of insect, the desired end product and considerations of cost and sustainability. Developing and implementing more effective and affordable methods, along with consumer education about the advantages of insects, can contribute to greater acceptance of edible insects as a nutritious and sustainable food source.

While the previously described approaches provide microbiological safety, they do not avert the re-contamination risk of the product in the following processing stages. Storage conditions will also play a crucial role in maintaining product quality with modified atmosphere packaging techniques, which have also been investigated to extend the shelf life of these items. Braide et al. 2011 have endorsed the use of modified atmospheric packaging for edible insect products to reduce microbial contamination and enhance shelf-life. Stoops et al. (2017) study examined two storage conditions, air and modified atmosphere packaging (60% CO₂/40% N₂). Storage in a modified atmosphere significantly reduced bacterial growth compared to storage in air, helping to maintain low microbial numbers during 35-day storage, suggesting a potential for extended shelf life, which is attractive to retailers and consumers and supports the feasibility of producing insect-based minced meat-like products with low microbial counts.

However, several technological challenges hinder the mass adoption of edible insects. According to Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro (2019), these challenges can be grouped into: processing and conservation of edible insects require efficient and affordable technologies to ensure safety, nutrition, and consumer appeal; sanitary quality issues arise from bulk sales without proper hygiene, leading to contamination (Gałęcki, Bakuła, and Gołaszewski 2023); post-harvest technologies are crucial for conservation, processing, distribution, and storage (Tyagi et al. 2019); drying techniques can lead to contamination, while microwave drying can negatively affect sensory quality (Parniakov et al. 2022); lipid oxidation is a problem in high-fat products (Bernardo and Conte-Junior 2024); domestication of insect species is limited, and transitioning from wild harvesting to agriculture is necessary (Raheem, Carrascosa, et al. 2019).

Production costs are high, hindering mass adoption of product and ingredient development, which requires innovation in formulation, extracting functional ingredients, and adapting to consumer preferences. Developing more efficient and cost-effective extraction technologies is essential for harnessing the functional potential of insects (Melgar-Lalanne, Hernández-Álvarez, and Salinas-Castro 2019). Also, adapting to consumer expectations and encouraging regular consumption is essential for successful insect production.

The mitigation of chemical pollutants in edible insects necessitates a thorough, multi-faceted strategy encompassing source management, agricultural techniques, processing methods, and regulatory measures. The process begins with source control, where the selection of feed and water is critical. High-quality feed must be free from contaminants such as pesticides, heavy metals, and harmful residues. The implementation of traceability systems ensures that the origin of feed and water can be verified, especially when agricultural byproducts or recycled substrates are used (FAO 2021). Water used in insect farming should also undergo regular testing for pollutants, including heavy metals and nitrates, to prevent bioaccumulation in the insects and protect consumers (Cardoso et al., 2023). Rearing and farming practices play an essential role in mitigating contamination risks. Regular environmental monitoring of the rearing environment, including soil, air, and substrates, is necessary to detect pollutants, particularly in open-air systems (Van Huis, 2021). Farms should be located away from industrial zones and polluted water sources to avoid contamination risks. Adhering to Good Farming Practices (GFP), including maintaining strict hygiene, effective waste management, and minimal use of approved pesticides, ensures a controlled and safe farming environment (Zhou et al. 2022). At the processing and handling stage, insect safety is further ensured through decontamination techniques. Pre-harvest cleaning, or purging, involves feeding insects contaminant-free diets for 24–48 h before harvest to expel toxins from their digestive systems (Liang et al. 2024)). Post-harvest techniques such as blanching, steaming, or organic acid washing effectively reduce pesticide residues, microbial contaminants, and surface-level toxins (Zhou et al. 2022). Additionally, magnetic separation or sieving is used to remove any potential metal fragments from processing machinery, ensuring physical safety (Lalander et al., 2019).

Lastly, regulatory and testing protocols are essential for ensuring compliance with safety standards. Routine testing for contaminants such as heavy metals (lead, cadmium, arsenic), pesticide residues, mycotoxins, and dioxins is necessary to meet international food safety regulations, including those outlined by Codex Alimentarius and EFSA (Van Der Fels-Klerx et al. 2018). Proper record-keeping of testing and traceability data further supports transparency and helps with regulatory audits. These combined practices help safeguard the quality and safety of edible insect products, ensuring they meet stringent food safety standards (IPIFF, 2024).

Additionally, identifying and controlling hazards at every process stage, from rearing to packaging and storage, is essential for producing safe, high-quality food. The effective

implementation of good manufacturing practices, prerequisite programs and HACCP is fundamental to ensuring the production of safe, high-quality insect-based products.

Conclusion and perspectives for the future

The global demand for novel sustainable food solutions continues to grow, driven by the pressing need to address the environmental and resource-intensive challenges of conventional animal farming and agriculture. As the global population rises, expanding food production without exacerbating environmental degradation poses a monumental challenge. In this context, investing in research and development for the safe rearing, processing, and marketing of edible insects emerges as a promising solution. Ensuring the safety of edible insects requires a multifaceted approach, encompassing microbiological, chemical, and allergen risk assessments, alongside effective legislative frameworks. Even though a surge in research articles relating to the safety of these innovative products has been observed, cohesive, data-driven conclusions are still scarce. The importance of microbiological studies focused on assessing the microbiological quality and stability from rearing through processing to storing the final product is fundamental. Contamination risks, especially with spore-forming bacteria, necessitate robust heat treatments and monitoring storage conditions to prevent germination in final products. Additionally, mycotoxigenic fungi and their associated mycotoxins highlight the importance of stringent control measures during rearing and processing. For chemical risks, factors such as rearing substrates, feeding regimens, and geographical differences influence contamination levels, emphasizing the need for standardized protocols and further research. Reared insects have a lower probability of chemical contamination than wild-catching insects since all life cycles are carried out under controlled and standardized protocols. Bioaccumulation of chemicals is less probable for arthropods with short life cycles, comprising a lower risk in terms of food safety. Allergenicity, particularly cross-reactivity with crustacean and house mite allergens, underscores the importance of comprehensive labeling, allergen identification, and processing studies to mitigate risks for sensitive populations. Once again, the scarcity of studies focused on actual species-specific allergens is still the norm, with cross-reaction with other arthropod studies being more common. The effect of processing, especially heat treatment, is also important to assess since it can interfere with the allergen function.

Existing food hygiene legislation provides a strong regulatory framework for edible insects; however, harmonization across regions and developing insect-specific guidelines are imperative. The integration of product-specific control strategies—such as freeze-drying, roasting, and other thermal treatments—has shown promise in reducing microbial loads and enhancing the safety of insect-based products. These measures must be continuously evaluated and refined to address emerging risks and support consumer confidence. Although significant progress has been made in identifying and mitigating risks, cohesive and data-driven conclusions remain limited. Comprehensive studies encompassing diverse

batches, rearing substrates, feeding regimes, and seasonal variations are essential for building a robust safety framework. This interdisciplinarity extends beyond research, requiring collaboration between academia, industry, policy-makers, and regulators to align safety protocols with market demands. Although entomophagy is still new to Western industries, edible insects represent a transformative opportunity to address food security challenges while advancing sustainable development goals, as outlined in the United Nations' 2030 Agenda. The successful integration of these novel foods into global food systems depends on ensuring their safety through scientific rigor, legislative alignment, and public trust. With concerted efforts, the edible insect industry has the potential to redefine sustainable food practices and contribute significantly to a resilient and equitable global food supply.

Authors contributions

Teresa Bento de Carvalho: Writing—original draft, Writing—review and editing, Visualization, Methodology, Conceptualization. **Paula Teixeira:** Writing—review and editing, Visualization, Validation, Supervision, Conceptualization. **Joana Bastos Barbosa:** Writing—review and editing, Methodology, Supervision, Validation, Conceptualization.

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