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REVIEW ARTICLE

Overcoming obstacles in insect utilization

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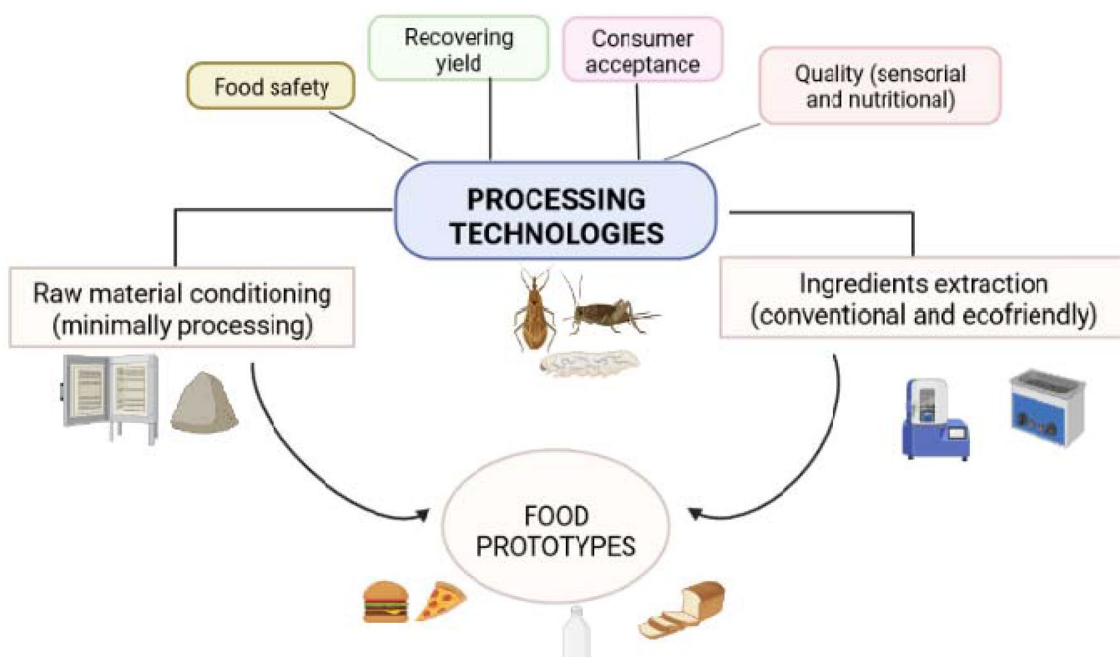
Abstract
Edible insects have long been part of human diets in some countries, and they are expected to become an important alternative food source because of their nutritional value and favorable environmental impact. However, insects' consumption safety and consumer acceptance are still significant barriers to market positioning, mainly in Western regions. Therefore, several processing technologies have been applied to develop insect-based food products and derivatives to increase consumer safety, shelf-life, and sensorial properties, including appearance. The processing pathway for insects as food might then be focused on eliminating such concerns. However, even though there is enough information related to processing techniques for edible insects, the use of the treated material has been limited as a substitute rather than a main constituted nutritional component. Moreover, there is little information about novel technologies and uses of insect derivatives compared to the minimally processed insect, as in the case of flours. This review presents the food safety (biological and chemical hazards) and cultural aspects of difficulties of eating insects and the role of processing raw material, extraction of insect derivatives (lipids and proteins), and food prototypes development on safety and consumer acceptance.

Graphical abstract



Keywords Edible insects · Food safety · Consumers acceptance · Processing technologies

Extended author information available on the last page of the article

Introduction

Currently, the main concerns related to the United Nations projections about the global growth population in 2030 (about 8.5 billion humans) are the impact on the food supplies and the environment (United Nations 2015). One of the principal food sources is the land, meaning that inappropriate use of natural resources such as water and fossil energy might negatively affect productivity [1]. Pimentel and Pimentel (2003) analyzed the required inputs for protein production for meat and plant-based diets in terms of sustainability. In this report, the authors pointed out the efficiency of both sources. For instance, an average of 25 kcal of fossil energy to produce 1 kg of protein and 100,000 L of water for 1 kg of fresh beef are required compared to 2.2 kcal and 5400 L for 4 kg of grains [2]. In this context, the Food and Agriculture Organization of the United Unions (FAO) has encouraged the generation of knowledge and work on more sustainable sources for food population demands, in specific the use of edible insects, which are appreciated due to their low environmental production impact, high feed conversion rates and nutritional value [3].

Extensive insect biomass worldwide, with more than 2000 edible species, has been recorded. Considering the global interest in food security and sustainability, the use of edible insects as a nutritional, available, efficient, and low-cost alternative source for food and feed is increasing [4].

Even though most of their food composition can vary depending on several intrinsic (species, stage of life) and extrinsic factors (feeding, harvest conditions, environment), the nutritional quality of edible insects is well-recognized, mainly due to considerably high amounts of macro and micronutrients, such as proteins, fats, minerals, and vitamins. It has been reported that daily requirements for vitamins and proteins in human diets could be covered by caterpillars [5]. An analysis of the nutritional composition of six edible insect species (*Rhynchophorus phoenicis, Bombxy mori, Acheta domesticus, Ruspolia differens Tenebrio molitor* and *Periplaneta americana*) showed the protein as the highest macronutrient (10–70%), followed by lipids (18–46%) and high amounts of calcium, potassium, magnesium, iron minerals, and vitamins, such as ascorbic acid, riboflavin, and niacin ([6].

Ghosh et al. (2017) reported that larvae (*Allomyrina dichotoma, Protaetia brevitarsis, Tenebrio molitor lavae),* and *adult (Teleogryllus emma, Gryllus bimaculatus*) proteins met the FAO (2003) recommendations intake of valine, isoleucine leucine, threonine, lysine, phenylalanine, and histidine essential amino acids, and these amounts were also comparable to other animal proteins [7]. However, in the case of lipids, a considerably higher content of polyunsaturated fatty acids (PUFA) in *Hydrous cavistanum* (726 mg/100 g) and *Acheta confirmata* (2883 mg/100 g) [8] compared to ranging amounts from 56 to 91 mg/100 g in different fish oils [9] has been reported. Similarly, high amounts of monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) were found in *G. sigillatus T. molitor*, mainly higher in palmitoleic acid, oleic acid (omega 6), linoleic acid, and α-linolenic acid (omega 3), respectively [10]. The presence of α-linolenic acid (omega 3) in *Tenebrio molitor, Alphitobius diaperinus, Acheta domesticus* and *Blaptica dubia* has also been previously reported by Tzompa-Sosa et al. (2014) [11].

Even though the introduction of edible insects as food by the industrial market has increased, entomophagy (the practice of eating insects) is still not well-accepted by most Western consumers in their diets due to different reasons headed by cultural aspects [12]. In this context of edible insect production and uses for food consumption and marketability as a novel food, according to the European Food Safety Authority (EFSA), several health risks (chemical and biological hazards) must be considered [13].

Besides the already approved insect species (*Tenebrio molitor*), others such as house cricket (*Acheta domesticus*), tropical house cricket (*Gryllodes sigillatus*), lesser mealworm (*Alphitobius diaperinus*), black soldier fly (*Hermetia illucens*), honeybee (*Apis mellifera*), migratory locust/grasshopper (*Locusta migratoria*) have been submitted for approval in 2020 [14]. Therefore, the necessity to transform the raw edible insects into safe and well-accepted food products is driven by the current efforts of food technologists, researchers, and academics; thus, this review is intended to address processing alternatives at present to deal with consumers acceptance of insect-based food products and their safety.

Food safety

Biological hazards

Food allergy is the human body's immune response after ingesting a specific type of food. This hypersensitivity to food gives rise to anaphylactic reactions that affect the human system at different levels, mainly skin and respiratory. The most recognized symptoms are hives, itching and flushed skin, eczema, urticaria, and difficulty breathing (asthma), which can cause severe health consequences. There are four types of immune reactions; however, the most occurrent one is type I (48%), known as IgE-mediated. The rest are categorized as IgE-independent (type I, II, III, and IV) when other cells, such as T, IgG, and IgM between others are associated [15]. The IgE antibodies reactions are incited by proteins or glycoproteins (protein + oligosaccharide) and their severity by the triggered reaction. However, other factors include allergen structure, physicochemical (solubility), and compositional features (molecular weight, amino acids profile). In addition, individual characteristics (genetics) influenced by environmental factors (degree of allergen exposure, lifestyle, diet) may influence the severity of symptoms. A cross-allergy is mediated by the immune response of these antibodies to analogous molecules (similar protein family) [16]. The muscle contraction in many invertebrate species such as crustaceans, mollusks, and insects is driven by a protein complex (troponin–actin complex) known as tropomyosin, which is considered one of the major allergens. However, the arginine kinase enzyme is also related to cross-reactivity immune response in Arthropoda (crustaceans and insects) [17].The homology between tropomyosin (amino acids profile) from crustacean shellfish and edible insects (house dust mites and cockroaches) has concerned the utilization of edible insects for food [18]. During the last years, edible insects have been considered a novel source of protein; however, it is crucial to consider studying their taxonomy to identify the hazards and risks of their consumption. Besides tropomyosin, a proteomic and bioinformatic study showed that the most extended protein allergens phylogenetically homologous in several edible insects and mollusks are chemosensory type proteins, hexamerin, and odorant-binding, which can cause an immune response in the sensitized population [19]. Some studies have shown phylogenetic homologies between proteins in *Tenebrio molitor* and arthropods, which have a high potential risk of causing allergic reactions after eating [20]. After ingesting fried larvae, the immunological test on an anaphylactic reaction in a man showed the presence of several sensitive proteins, such as tubulin, tropomyosin, hexameric, and chitin (no proteinaceous compound), between others. Another study was performed on allergic and non-allergic house dust mites and crustaceans' population (serum) to identify cross-reactive protein fractions. In this case, the primary identified protein fractions were tropomyosin (urea soluble) and arginine kinase (water soluble) within moderate stability to simulated pepsin digestion [21].The anaphylaxis reaction assessment to ingestion and inhalation of *T. molitor, Zophobas morio,* and *Blattella germanica* was carried out on non and hypersensitive individuals to insect products. Of seven patients, one showed sensitivity to *Tenebrio Molitor* in both tests [22]. Severe anaphylaxis was reported without a previous immunological response to arthropods showing cross-reactivity to some proteins such as hexamerin and tropomyosin found in mites and crustaceans [23]. However, no hypersensitivity was reported after a toxicological assessment on lyophilized *T.molitor* larvae using a murine model [24]. The dried *T.molitor* was considered by EFSA (EU) 2015/2283 panelists safe for human consumption except for the hypersensitive population to crustaceans and dust mites. Safety of dried yellow mealworm (*Tenebrio molitor* larva) as a novel food under Regulation (EU) 2015/2283.

Cross-reactivity between crickets, grasshoppers, locusts, and prawns has previously been shown, mostly due to arginine kinase allergen [25]. From the human consumption point of view, *Acheta domesticus* and *Locusta migratoria* are the most relevant to investigate, because they are in the authorization process as a novel food (NF) by the EFSA [26].The cross-reactivity of crustaceans, house dust mites, and flies to some edible insect's protein extracts and concentrated were analyzed. Crustacean-sensitive patients' sera showed IgE to bind to desert locust and house crickets' legs proteins and migratory locust and house dust mites. However, the study showed that the immunologic mechanism might reduce by applying adequate processing [27]. An immune test (ELISA) performed on shrimp allergic patients after ingestion of *Gryllus bimaculatus* showed correlated responses; the similar allergen identified was tropomyosin [28]. Similar findings are reported with IgE cross-reactivity with tropomyosin in *A. domesticus*, and shrimp protein extracts enriched biscuits with crickets' protein showed tropomyosin stability to simulated gastric digestion [29].

More than 200 foodborne diseases can be caused primarily by bacteria, viruses, or parasites; however, other harmful substances such as chemicals, toxins, and heavy metals are also considered unsafe. The hazard risk assessment might be applied to the entire chain production of the listed ingredients used in a product for human consumption. Foodborne diseases are one of the leading public health problems in the world. The most common pathogens identified are *Escherichia coli, Staphylococcus aureus Listeria monocytogenes, Campylobacter spp. (jejuni, coli* and *lari), Bacillus cereus* and *Vibrio parahaemolyticus* and in the case of parasites Cryptosporidium, Cystoisospora, and trematodes [30]. The most common foodborne diseases in Europe are caused by *Salmonella spp., Campylobacter spp.,* and *L.monocytogenes* [31]. One of the most reported viable pathogens (natural loads ~ 8 log CFU) in *Tenebrio molitor*, which the EFSA already accepts as a novel food, is *Salmonella spp*. Other animals can quickly spread these enterobacteria into the environment affecting the soil and water, and thus, contaminated sources could affect mostly wild insects. Even though pathogenic microorganisms can contaminate both natural and raised insects, it has been reported that their safety for human consumption is highly affected by the harvesting technique (wild or reared), their feed, and how they are processed. The main concerns on naturally produced insects are their uncontrolled feeding which can give rise to higher levels of toxins, and the hygienic practices they are accustomed [32]. Even in reared insects, a microbial assessment in *Acheta domesticus, Gyllodes sigillatus,* and *Tenebrio molitor larvae* showed considerable variation in the microbial accounts between the origin of the batches. However, in their study, no *Salmonella spp. and L. monocytogenes* were detected [33] *L. monocytogenes* loads were measured at different processing steps (fasting, washing, and cooking) on contaminated yellow mealworm biomass. The washing step did not affect the microbial load; however, it significantly reduced after 24 and 48 of fasting, and no pathogens were found after cooking [34]. In addition, a study was carried out on substrates (Nutrient aga) with *Tenebrio molitor* larvae, and single larvae (disinfected and non-disinfected using 70% ethanol solutions and twice washed with Milli Q water) using different loads of *Salmonella Typhimurium* (1.7 to 7.4 log CFU/g) was monitored for 14 days. During the entire period, all substrate samples showed lower amounts for the quantitative limit level of detection (1 o 2 log CFU/g). However, in the single non-disinfected larvae, around 1.9 log CFU/g values were found. Nevertheless, in disinfected single larvae, except for the lower load (1.7 log CFU/g), positive results for *Salmonella* were reported (2.3 ± 0.2, 2.0 ± 2.0, and 3.7 ± 0.1 log CFU/g). These results indicate the importance of reducing the initial load of the material to be successful within the following sanitation procedures [35]. A comparative study showed that the major bacteria and fungi found in *Tenebrio molitor, Acheta domesticus, Locusta migratoria, and Alphitobius diaperinus,* were *Bacillus cereus, Clostridium* and *Staphylococcus* and *Aspergillus and Penicillium* (mycotoxin-producers) [33]. Galecki et al. (2019) found that 80% of the evaluated farm producers of mealworm, house crickets, Madagascar hissing cockroach, and migrating locust insects farmed in different countries (Czechia, Germany, Lithuania, Poland, Slovakia, and Ukraine) showed the presence of parasites in both their microbiota and bodies. Approximately 68% of them were pathogenic for insects (*Nosema spp, Gregarine spp., Nyctotherus spp., Steinernema spp., Gordiidae, H. diesigni, Thelastomidae, and Thelastoma spp.)* and 30% potentially harmful for humans and animals (*Cryptosporidium spp. Isospora spp. Balantidium spp. Entamoeba histolytica and E. invadens*) between others [36].

Chemical hazards

Agricultural waste recycling by insect larvae bioconversion has been extensively reviewed as a sustainable alternative for producing added-value products. However, concerns about their accumulation of chemical compounds (coming from feeding) and human health risks have risen. The importance of studying the bioaccumulation of chemicals such as heavy metals, pesticides, and the presence of plant toxins, among others, in potentially approved insects for human consumption has also been underlined (EFSA). One of the main problems is that there are no established permissible limits for most chemical hazards on insects for human consumption; therefore, most literature reports their detection and quantification and compares them to the allowed values in other commodities. Chemical hazards of 51 insect-based (silkworm) commercial samples (powder, flour, protein bars) from crickets and the entire insect were evaluated. Arsenic, lead, cadmium, and mercury were detected in all samples; however, due to the absence of insect product regulations, the authors based their results on the Codex Alimentarius Commission for brown rice; in this context, only cadmium exceeds the maximum levels established. In the case of pesticides, five products (4 crickets and one silkworm) exceeded the standard maximum residue limit (MRL) for food products (0.1 mg/kg), mainly in glyphosate (herbicide) and AMPA (a metabolite of glyphosate) [37].

The agricultural side streams have been proposed to use as a substrate for insects' rearing; however, some pesticides used during crop farming could be transmitted to them. Houbraken et al. (2016) intentionally exposed *Tenebrio molitor* larvae to contaminated carrots with pesticides for 48 h. Even though the residues of pesticides highly diminished after larvae were starved (24 h), the authors encourage monitoring these compounds in plant-based waste reared insects for human purposes because of the initial values of octanol–water partition coefficient Log (Kow) and their excretion rate [38].

A review of the mycotoxins and heavy metals in insects attempted for food and fed reported the bioaccumulation of arsenic, cadmium, lead, and mercury, mostly in *Hermetia illucens* larvae and in lower amounts in *Tenebrio molitor*. However, no accumulation of mycotoxins and polycyclic aromatic hydrocarbons was observed [39]. The mycotoxins are secondary metabolites produced by fungi kingdom organisms and transmitted to crops and animals by the environment; then, the exposure of insects to natural living conditions potentially increases their contamination risk [40]. The same study described that the mycotoxins in the insects might be degraded by their metabolism. A review of accumulation and biodegradation of mycotoxins in insect larvae from Diptera (flies), Coleoptera (beetles), and Lepidoptera (butterflies, caterpillars) orders reported lower values of mycotoxins than the maximum levels (MLs) allowed by the legislation for feeding and most of them lower in detection and quantification (LOD, LOQ) levels [41]. When comparing the levels of some chemical contaminants such as dioxin and pesticides, among others) heavy and metals (Cr, Cu, Ni, Pb, Sn, As, Cd, Co, Zn) in edible insects/marketed insects food products (in Belgium) and animal products, lower amounts of chemical fractions and similar values of As, Co, Cr, Pb and Sn than in fish and meat were found [42]. Due to the chemical hazards depending on harvesting or rearing condition rather than their processing, this topic will not be covered in this review.

Cultural aspects in consumption of insect acceptance

The diet is one of the most affected aspects of human behavior influenced by culture. For some people, certain foods can be considered delicacy and others unpleasant or even forbidden (because of religion). The consumption of insects by human beings, known as entomophagy, has been a worldwide practice, mainly in Latin America, Asia, and Africa. Its use as food has been promoted due to increased population growth, food demands, sustainability (green gas emissions, use of natural resources, such as soil and water), nutritional composition, and production efficiency. The culture, climatic conditions (geography), availability, and necessity (low incomes) have driven populations to consume insects as a primary local diet. Nowadays, edible insects for food and feed have gained the attention of communication media, researchers, the food industry, and international organizations (FAO) as a viable alternative to ensure global food security [43]. The entomophagy acceptance in Western societies has been appointed to the population's unfamiliarity. Insect rearing has been considered primitive practice, and insects as pests. In addition, some population sectors have expressed fear of damaging their bodies (risk perceptions, such as disease transmitters, unhygienic, allergies) or having an unpleasant experience. The acceptance of eating insects could be defined by the degree of food neophobia (rejection of unfamiliar food) and the food motives profile (novelty, nutritional benefits, reduction of environmental impact) [44]. One of the main issues for Western consumers is the visualization of the insect shape on the food, which is not perceived as a usual diet element. The insect-based product appearance plays an important role in the customer's purchase decision. The risk perception of eating processed insect-based products decreases compared to an unfamiliar food (whole insect). Using difficult-to-visualize insect materials positively impacts the population's mindset [45]. The customer's awareness about the consumption of healthy products can also determine their purchase decision. The nutritional label or ingredient list in processed insect products might influence the consumer's choice [46].

A study reported on the Belgian consumers' willingness to eat insects or insect-based ingredients and their perception of being incorporated into different meals. Most participants perceived them as appetizers (culinary prepared), followed by adding in main dishes, and the lower scores were obtained for their use in salads, soups, or in their natural shape [47]. Commercial *Tenebrio molitor L.* and crickets *Acheta domesticus* were used to prepare snack bars (insect meal and whole insect). Based on their results, the authors concluded that the visualization of the entire insect was the main factor in the lowest acceptability scores [48]. Orsi et al. (2019) reported that German consumers were more willing to taste an insect-based burger than the whole worm; however, food aversion was the main predictor of product acceptance, although the participants were intensely aware of their sustainability compared to other high-nutritional products [49]. Even though pizza consumers preferred the original pizza, an acceptability study on using crickets as flour in their elaboration obtained good sensory attribute scores, concluding that neophobia is more influenced by the ingredients' nature rather than a new product showing interest in functional foods and health benefits [50]. Even though global marketing on willingness and familiarity with insects' consumption in Europe is increasing, consumer approval is still the major problem to solve.

Edible insect processing pathways

Several methodologies have been applied to assure food safety and quality, depending in most cases on the prevalence of safety risk and the final intended consumption of the commodity. Conventional methods (using thermal treatments) such as boiling, blanching, and drying have been mostly used for reducing microbial loads and prolonging their shelf life. In the case of physical methods, such as extrusion, are applied to improve the sensorial attributes (mainly texture) and acceptability of products. Furthermore, in the case of environmentally friendly and more efficient technologies (green), more extensively reviewed methods are reported (microwaves, pulsed light, HPP, among others) mainly based on the interest of reducing the residues (mainly solvents), reducing nutritional loss, and increasing yield.

Besides these reasons, other alternatives, such as enzymatic hydrolysis and fermentation, are used to reduce allergenicity and enhance nutrient bioavailability. The application of these methodologies is not number limited (one or more can be applied), typically depending on the purpose of the material treated for the food prototype developed and its outcome. In this regard, it is essential to know the type of processing that might impact more on consumers' acceptability and legislation requirements for insect products or insect food ingredients. In 2019, a new system classification for processed food based on health considerations rather than the technology was published. This system called NOVA classification includes 1) Unprocessed and minimally processed foods, 2) Processed culinary ingredients, 3) Processed foods, and 4) "Ultra-processed" foods. This classification has been a very controversial and confusing approach for the industrial sector. For instance, for the first group of minimally processed products, the processing techniques include roasting, boiling, pasteurization, refrigeration, chilling, and freezing, among others. In the case of processed food (group 3), canned or bottled vegetables, legumes, and salted or sugared seeds are considered. In addition, yogurt is treated as an ultra-processed food in this classification if sugar or another additive is added [51].

In this article, based on the operational technique of processing, minimally processed will be considered the conditioning and preparation of material (physical procedures such as cutting, milling, and reduction of water activity, among others), disinfection (washing) for their convenience storage (freezing, chilling) and distribution (packaging such as modified atmospheres) [52], food ingredients as extracted compounds from the conditioned material and food prototype a developed product either using pre-treated material or derivates.

Raw material conditioning

The application processing techniques using heat such as blanching, pasteurization, sterilization, and drying have been extensively applied to eliminate or reduce to allowed levels the biological hazards in food.

Vandeweyer et al. (2017) studied the effect of blanching followed by refrigeration storage on *Tenebrio molitor* larvae microbial loads. The authors observed that after 10, 20, and 40 s of blanching time (excepting endospores), the total amount of Enterobacteriaceae, lactic acid bacteria, yeasts, molds, and psychotrophs decreased (≤ 3.5 log cfu/g) and no successive growth occurred during their cold storage (6 days). Nevertheless, none of the combined methodologies eliminated the presence of endospores [33].

A study compared the microbial load on differently processed edible insects (*Acheta domesticus, Locusta migratoria, Alphitobius diaperinus, Tenebrio molitor, Apis mellifera, and Hermetia illucens,* among others). It was found that cooked and deep-fried insects had lower bacterial counts than dried (powered), which were above the recommended amounts of bacteria and contained some pathogens (*B. cereus, coliforms, Serratia liquefaciens, Listeria ivanovii, Mucor spp., Aspergillus spp., Penicillium spp., and Cryptococcus*). Notwithstanding, the above-mentioned results underlined that subsequent contamination could occur after processing [53].

Regarding the insect's allergenicity, heating processing methods might affect the structural characteristics of proteins influencing the IgE antibody binding reactions and their ability to trigger its production [54]. Lamberti et al. (2021) tested the effect of boiling (5 min at 100 °C) and frying (3 min at 180 °C in sunflower oil) thermal processing on IgE cross-reactivity of buffalo worm and mealworm larvae, crickets, and grasshoppers' allergens. Sera of sensitized allergic patients (shrimp, house dust mites, and mealworm) were used for immunoassays. Although decreased cross-reactivity after grasshoppers boiling was found in shrimp allergic patients, frying eliminated the immunorecognition. Similarly, no reactions were observed on dried buffalo worm larvae. The authors attribute these results to changes in protein conformation which may affect their solubility (water-soluble and insoluble fractions) primarily in Troponin T and B actin proteins [55].

It has been shown that insect processing has also influenced consumer acceptance. Using and image of seasoned rice prepared with insect powder positively impacted the opening attitude of tasting the products in contrast to the image of rice cooked with the whole insect [56].

Insect derivatives

As previously mentioned, insects are a good source of proteins, lipids, carbohydrates (fiber), and vitamins. Therefore, several publications have been focused either on starting material (flours) composition or material pre-treatments for compound extraction, mainly for yield increase, quality preservation (nutritional and functional), and solvents use reduction (eco-friendly methods).

Besides their nutritional contribution to human diets, protein is appreciated as an additive in the food industry due to its functional properties as an emulsifier, stabilizer, and gelling agent, among others. Minimally processed material (insect flours) is typically used for protein concentrate and isolates, following protein solubilization and recovery methods. However, the defatting step could also be included in the protein extraction procedure. Some functional properties of insect protein concentrates (*Tenebrio molitor and Gryllodes sigillatus*) from insects' flour were compared to pea and whey proteins. Both insect species were found to have higher fat adsorption capacity (214% and 328%) compared to pea and whey protein (138% and 204%). Stone et al. (2019) evaluated the quality and functional properties of protein concentrates extracted from commercial crickets and mealworm powders. Mealworm and crickets showed 0.71 and 0.85 amino acid scores and lysine and tryptophan as limiting amino acids, respectively. Crickets presented good foam capacity and stability (higher than 80%) contrary to mealworms, in which no foam formation was observed. The quality and some functionalities such as protein-concentrate water and oil holding capacities were like pea and fava proteins. Even though insect's material showed low solubility values and mealworms did not exhibit good foam properties, the authors underlined their possible uses, where the solubility does not determine the product quality, such as meat products, bakery, and snacks [57]. *Hermetia illucens* have also been reported as good foaming and emulsifier agents compared to WPI [58]. Some eco-friendly methodologies have also been reported; subjecting *Bombay locusts* powder to ultrasound treatments improves protein yield and solubility. However, high ultrasounds amplitudes have a negative effect on protein foaming properties; the authors stated that moderate treatment might help enhance protein functionality [59]. Smetana et al. (2020) reported that more sustainable treatments such as pulsed electric field (PEF) could be used for insect biomass pre-treatments to increase protein concentration (*Tenebrio molitor* larvae) because of the cell permeability disruption [60]. In the case of fat extraction, the lipids yield, and fatty acids profile might depend on the insects' composition and diets. According to their physical state, lipids usually are divided into oil (liquids at room temperature) and fats (solids at room temperature). From this perspective, the physicochemical features of insect lipids and extractions methods might be addressed for food applications. Liquid and solid fractions obtained in dry fractioned mealworm lipids showed differences in color, melting, and crystallization points. The authors pointed out that they could be used in food products such as dressings and mayonnaise due to their lighter color and fluid state of liquid fractions. In contrast, solid fractions would be better used for spreading products [61].

Pressurized-liquid extraction increased the lipids yield of freeze-dried *T. Molitor* and *Acheta domesticus* compared to organic solvents (ethanol, and ethanol:water (E:W) and ultrasound-assisted extraction (UAE), however, enhanced nutritional composition (PUFAS) in UAE and E:W was found [62]. Furthermore, although higher lipid yields from *Tenebrio molitor, Alphitobius diaperinus, Acheta domesticus,* and *Blaptica dubia* insects by lab method (Folch) compared to industrial methods (aqueous and organic solvents), better fatty acids profile (ω-6/ω-3 ratio) was observed in aqueous processing [11].

Food prototypes

As was mentioned before, acceptance of eating insects is one of the main issues to address to move forward. In this context, to avoid the rejection due to the visuality of the entire insect, the insects should be processed, since derivative ingredients are associated with increased consumers openness [62]. Several insect materials and ingredients differently processed have been reported for food prototype development. Due to protein functionality already discussed, insect-derived materials (high protein content) and insect protein have been used as extenders in developing meat-based products, such as sausages, burgers, and patties. Some of their reported abilities in these products are an improvement in texture, water, and oil capacity and appearance, among others [63]. Different processing parameters (heating time and amount of added $CaCl_2$) were used to prepare insect-based-meat prototypes using *Alphitobius diaperinus* protein. This product showed a 74% yield of curded protein, and at 100 °C using 20 mmol of $CaCl_2$, the insect protein's gelling properties allowed the formation of large clusters and stranded structure, with a good texture and desired mouthfeel to be used as meat replacer [64]. Frankfurter sausages prepared with 10% yellow mealworm powder did not show differences in cooking loss, texture, emulsion stability, and overall acceptability [65]. Although oven-dried grasshopper (*Sphenairum purparascens*) powder resulted in a suitable meat binder for starch substitution in sausages, the product was not well-accepted by consumers due to its unfamiliar texture, smell, and taste [66]. These results confirm that applied processing methodologies on either materials or ingredients from insects significantly impact final product features (safety and sensorial) and thus its consumer's acceptability.

A comparison of chemical characteristics and microbial stability on fermented non-defatted mealworm pastes prepared with fresh and pre-treated material (steamed, cut under vacuum, and ground) was carried out. It was found that viscosity and color were not affected during the storage (chilling and freezing); nevertheless, from the microbial point of view, refrigeration temperatures did not ensure the microbial safety of the product without preservatives addition [67]. Cho et al. (2018) compared fermentation characteristics and sensorial perception of the fermented soy sauce and microwave-dried *Tenebrio molitor* larvae (defatted and non-defatted). The non-defatted insect sauce presented higher amounts of total free amino acids, and except for one soy sauce blend (bitter taste), no differences in overall acceptance were reported [68].

Supercritical CO_2 extracted lipids from black soldier fly and mealworm were used as substitutes for fat (palm fat) and oil (canola oil), respectively, in margarine production. The final product showed higher yellowish coloration than the traditional product; however, good spreadability at refrigeration and room temperatures was reported [69]. Good sensory attributes and the overall food experience scores were found in hummus and cracker products prepared by total and partial vegetable oil substitution using deodorized yellow mealworm oil compared to crude oil [70]. Similar consumers' acceptance results on deep-fried potatoes with yellow mealworm oil (crude and deodorized) were also reported. The authors concluded that eliminating some volatile compounds from insect's oil (intense off-flavors) positively impacts the consumer's acceptance [71].

Black soldier black fly fat was used as a butter substitute in some bakery products (cake, cookies, and waffles) at 25% and 50% (w/w). When products were replaced with 25% of insect's fat, a positive consumer's global experience and affinity product besides structure and functionality was reported compared to products with butter. Moreover, the authors underlined that products with higher amounts of refined insect fat could also have a better consumer preference for avoiding rancid aromas and off-flavors [72].

Table 1 Processing technologies and uses applied to whole insects and their ingredients

Insect species	Processing technologies	Use	Company	References
Flour	Conditioning			
Tenebrio molitor Alphitobius diaperinus	Freeze-drying Grinding Elimination of appearance	Biscuits	Kreca Ento-Feed BV, Netherlands	[74]
Hermetia illucens larvae *Mealworm beetle*	Freeze-drying Milling under vacuum	Bread	https://bioflytech.com/la-compania/ http://www.insectside.com/	[75]
Tenebrio molitor Acheta domestica	Insect starving Blanching Convection-drying	Energy bars	Pet shop	[76]
Tenebrio molitor	Convection-drying Pre-treatments: UV exposure Pasteurization Sterilization	Prebiotic	https://tracxn.com/d/companies/insagri.com	[77]
Tenebrio molitor	Microwave-drying Grinding Sieving	Extruded snacks	HaoCheng Mealworm Inc	[78]
Tenebrio molitor	Convection-drying Grinding	Extruded meat analogous	M.G Natural	[68]
Tenebrio molitor	Fasting freezing	Burger patties Beef burger	Laboratory reared	[47]
Protein	Extraction			
Acheta domesticus	Conditioning: frozen- aqueous blended pasteurization Enzymatic hydrolysis Freeze-drying	Tortillas and tortilla chips	https://www.ovipost.com/	[79]
Ascra cordifera *Ascra cordifera*	Conditioning: starving freeze-drying, grinding, defatted Isoelectric precipitation Freeze-drying	Emulsions	Wild harvested ProEnto S.A.P.I. de C. V	[80]
Hermetia illucens	Conditioning: powdered (no specifications) Isoelectric precipitation Freeze-drying Milling Defatting	Emulsions	https://hexafly.com/	[81]
Tenebrio molitor Acheta domestica	Conditioning: dried (no specifications), ground (liquid nitrogen), defatted Drying (nitrogen stream) Chemically extracted (PBS buffer) Vacuum filtrate Freeze-drying Acid-hydrolysis	Pasta	https://inef.it/	[82]
Lipids	Extraction			
Acheta domesticus *Tenebrio molitor*	Conditioning: freeze-drying, grinding, defatted Ultrasound-assisted extraction Pressurized liquid extraction	Maintaining oil quality profile	Animal Center SL, Valencia, Spain	[62]
Tenebrio molitor	Conditioning: microwave-drying, No-grinding low temperature Compression	Oleogels for cookies	http://www.hyunmyung.co.kr/company_eng.html	(Kim and Oh 2022)

Table 1 (continued)

Insect species	Processing technologies	Use	Company	References
S. gregaria *R. differens*	Conditioning: freezing, cutting, boiling Aqueous extraction	Cookies baked	Animal Rearing and Containment Unit (ARCU) of the International Centre of Insect Physiology and Ecology (icipe), Nairobi, Kenya	[84]
Hermetia illucens *Tenebrio molitor*	Conditioning: No indicated Supercritical CO_2	Margarine	https://hipromine.com/our-products	[69]

Insect-based milk analogue using frozen *Tenebrio molitor* larvae and pre-treated for enhanced nutrients release (PEF) was standardized with larvae fat extracted by supercritical CO_2 method, sunflower lecithin (as emulsifier), and ascorbic acid as a preservative. Despite this product having a low protein content (1.19%) compared to cow milk (~3.5%), the authors concluded that it was a successful method for developing this prototype; however, they encourage formulation improvement and insect-milk products alternatives investigation [73].

Even though, in 2015, the European Union (EU) allowed the commercialization of edible insects and their ingredients for human purposes as a novel food, the new regulation (2018) forced all European countries to apply and wait for their approval, excepting the products launched before the mentioned year. Therefore, the international platform of insects for food and feed (IPIFF) announced (*Production and commercialization of insects as a novel food in the European Union Conference, 2020*) that the 64 members (insect producers) from 23 worldwide and 20 European countries (The Netherlands, Belgium, Ireland, UK, France, Spain, Denmark, Norway, Sweden, Russia, Lithuania, Latvia, Poland, Ukraine, Germany, Switzerland, Austria, Bulgaria, Croatia, and Italy should support the implementation of the legislation, standards and good practices (https://ipiff.org). At present insects' market is led by the whole insect, followed by bars and snacks; however, it is expected to increase for functional food, baked products, and meat analogues in 2025.

After the primary production of insects (farming), several processing technologies are applied for their commercialization. As Table 1 shows, not a single technique is used, and usually, some minimal processing must be applied mainly from the food safety point of view for microbial load reduction and shelf-life extension. However, these conditioning steps are also helpful for either appearance improvement in the final product and thus increase consumer acceptance or for ingredients extraction. In the case of insect-derived ingredients, the purpose is more related to increasing yield, decreasing environmental impact by reducing the use of solvents, and maintaining their nutritional quality (see Table 1).

Conclusions

The insect's safety and appearance perception as familiar food continue to be an obstacle in Western populations. However, the promotion of production edible insects commercially and their market share is still increasing in the market is still increasing. Recently, the publications related to edible insects as food and feed have significantly increased, especially in processing but mainly for raw material conditioning. Market companies offer mainly minimally processed (frozen, dried, powdered, among others) edible insect products for food purposes. In the case of insect derivatives, technologies and applications are less investigated. Using edible insect's nutritional compounds such as proteins, lipids, and carbohydrates for food products could be a better alternative for population acceptance. The study of insect additives could also extend their use in solid food prototypes (insect flours) and explore developing emulsions, beverages, and other applications, such as encapsulants. The production of edible insect additives can increase the potential for industrial exploitation in developing nutritious products as promising sustainable alternatives.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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