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REVIEW ARTICLE

Edible insect-processing techniques: a strategy to develop nutritional food products and novelty food analogs

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Abstract

Edible insects have been part of the eating habits of several cultures over the years. They are recognized as a promising nutritional and sustainable alternative food source. The transformation of insects into safer and more acceptable food ingredients depends on the processing techniques and the final food system. Conventional methodologies such as blanching, boiling, drying, and milling are primarily used for material pre-conditioning and powder preparation, mostly for preparing bakery products. Most advanced technologies are preferred for extraction of insect derivatives such as lipids, proteins, polyphenols, and chitosan due to their better-quality preservation, higher yield, and more environmentally friendly (solvent residues). Insect derivatives (mainly lipids and proteins) have been used to enhance the nutritional value of processed products and to produce food analogs, principally for meat and less investigated for milk and dairy products. This literature overview summarizes the effect of different processing techniques on edible insects' safety and quality and their use for the development of processed products and derivatives for food analogs production.

Keywords Edible insects · Insect processing · Insect-based food products · Insect derivatives · Insect-based food analogs

Introduction

The food demand is projected to increase drastically as the world population grows exponentially; the United Nations (UN) estimations for 2050 indicate nearly 10 billion people. This overpopulation requires more natural resources and food, compromising food security. Globally, the food systems currently use at least 70% of freshwater and nearly 50% of land resources, mainly for animal feeding. It is well known that livestock farming has the most significant GHG emissions in the food supply chain, besides their affection for soil erosion, deforestation, and water pollution. For instance, cattle produce 4.6 gigatons CO_2-eq, representing about 65% of the emissions [1]. The FAO estimates that the per capita consumption of animal protein will increase globally; thus, more animal-based production will be needed to meet human requirements [2]. In recent years, the food industry has introduced more sustainable protein sources for feeding and human consumption, such as biomass residues [3], microalgae [4], fungi [5], and, more recently, insects [6, 7]. The FAO has encouraged the use of edible insects as food due to their high nutritional value and environmentally friendly breeding conditions [8]. Some other advantages are that insect rearing has a high feed conversion efficiency and fecundity, low GHG and ammonia emissions, and less land, water, and energy requirements than poultry and livestock [9, 10]. In this framework, edible insects can be considered a sustainable alternative to contribute to food security, providing high-nutritional quality ingredients for food product development, especially in developing countries facing animal-based protein shortages, leading to malnutrition and growth deficiencies [11].

Entomophagy, which is the practice of eating insects, is a common feeding habit in several regions in Africa, Asia, and Latin America [12] compared to Western Europe, in which the edible insects are minimally cooked for direct consumption or used as ingredients to produce traditional dishes [13]. For instance, insect consumption in Mexico, which stands out as the country with more than 500 identified edible insect species, is culturally accepted and these species are mostly included in the gastronomic culture. The primary strategy to increase consumer acceptance

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is their conversion to a safe and familiar food product by processing. Minimal processing techniques such as drying and grinding have been used to produce material (mainly insect powders) incorporated in snacks [14], beverages [15], bakery [16, 17] and pasta [18] and meat products [19–21]. Also, insect derivatives, such as proteins, could be used as potential functional agents in the several food formulations due to their technological properties (emulsifying, gelling, foaming, water, and oil absorption) [10]. Nowadays, innovative food products formulated with edible insects are more acceptable and market-positioned, such as food analogs all over the world [22]. The production of food analogs aims to mimic or resemble a specific type of food, principally animal-based commercial products such as meat and meat derivatives and milk and dairy products.

Edible insects: a nutritious alternative for food security

Population growth has impacted food security primarily in low- and middle-income economies. Over 820 million people worldwide suffer from hunger, and almost 2.3 billion face food insecurity at moderate or severe levels [2]. Food insecurity is one of the most serious and widespread problems, substantially affecting people across developing nations [23]. The permanent availability, accessibility, and affordability of nutritious food is key for human well-being and is an international priority for vulnerable populations [8, 24]. Insects are pointed out as an economical and efficient alternative to prevent nutritional insecurity due to their composition, accessibility, and sustainability. In addition, insect rearing requires elementary techniques, and the growing rates are fast [8].

Humans currently consume several species of edible insects (over 2000) because of their taste and availability. The most consumed worldwide include Coleoptera (beetles, 31%), Lepidoptera (caterpillars, 18%), and Hymenoptera (bees, wasps, and ants, 14%), followed by other main species, including Orthoptera (grasshoppers, locusts, and crickets, 13%), Hemiptera (cicadas, leafhoppers, planthoppers, scale insects, and true bugs, 10%), Isoptera (termites, 3%), Odonata (dragonflies, 3%), Diptera (flies, 2%) [25].

Edible insects are recognized mainly as a good source of protein, lipids, and some micronutrients (vitamins and minerals); however, their nutritional profile may differ depending on their metamorphosis stages, gender, feed composition, habitat, environmental factors, processing and preservation techniques, and measurement methods performed [8, 26].

Insect proteins have been reported as highly digestible by humans [27] and balanced in most essential amino acids such as tryptophan, tyrosine, and lysine [28]. On average, the protein content on a dry basis varies between 35% (some species of Isoptera) and 61% (some species of Orthoptera) [29]. The highest protein noted is 77% in some of the Orthoptera species (*Melanoplus femurrubrum*) [28], and lipid content ranges from 9.12% (*Zonocerus variegates*) to 67.25% (*Homorocoryphus nitidulus*) on dry matter [30]. Some species of Lepidoptera (*Phassus triangularis*) have been documented to exhibit a lipid content reaching as high as 77% [28]. Lipids consist mainly of unsaturated fatty acids, including monounsaturated fatty acids (palmitoleic acid and oleic acid), polyunsaturated fatty acids (linoleic and α-linolenic acids); however, some species, such as black soldier fly (*Hermetia illucens*) is rich in lauric acid (saturated fatty acid). From different points of view, this derivative compound could be used to replace palm kernel oil ingredients in developing some food products and represent an alternative source of essential fatty acids, especially in countries with poor access to fish and fish-based food products [8]. Regarding the diversity of unsaturated fatty acid compositions in different insect species, Womeni et al. [30] investigated the composition of oils extracted from some species consumed in Cameroon, and the authors concluded that the primary fatty acids in termites (*Macrotermes* sp.) were palmitic acid (30.47%), oleic acid (47.52%), and linoleic acid (8.79%), in grasshoppers (*Zonocerus variegates*) were palmitoleic acid (23.83%), oleic acid (10.71%), linoleic acid (21.07%), α-linolenic acid (14.76%), and γ-linolenic acid (22.54%), and in caterpillars were palmitic acid (30.80%) and linolenic acid (41.79%).

Regarding micronutrients, edible insects have been considered a good source of complex B vitamins [31, 32]. Adult house crickets provide a valuable source of vitamin B_{12} (5.4 µg per 100 g), contributing to the recommended daily allowance (RDA) of vitamin B_{12} for adults (2.4 µg/day) [33, 34]. It has been reported that silkworm pupae are an excellent source of thiamin (0.07 mg per 100 g), riboflavin (2.23 mg per 100 g), and niacin (2.2 mg per 100 g). Silkworm pupae also contain about 10 mg of tocopherols per 100 g, which is a much higher level than that found in animal products such as milk (0.21 mg per 100 g), chicken (0.67 mg per 100 g) and pork (0.34 mg per 100 g) [35]. The escamoles, which are *Liometopum apiculatum* M ant eggs, have a high content of vitamins A, D, and E, containing approximately 505 µg/100 g of retinol, 3.31 µg/100 g of cholecalciferol, and 2.22 mg/100 g of alpha-tocopherol [36].

In the case of minerals, it has been found that iron content in Mopane caterpillars (*Imbrasia belina*) is higher (31–77 mm/100 g) than in beef (6 mg/100 mg) [37]. Similarly, locusts' species contain between 8 and 20 mg per 100 g [38]. Under this perspective, edible insects could contribute to iron daily intake and reduce its deficiency, mainly in low-income countries with limited affordability to meat. In addition, an investigation on the mineral content of four insects (*Bombay locust*, *Patanga succincta*, scarab beetle *Holotrichia* sp., house cricket *Acheta domesticus*, and mulberry silkworm *Bombyx mori*) has also shown not only high amounts of iron but also magnesium, zinc, and calcium [39]. Based on their analyses, Ghosh et al. [40] concluded that insects *Allomyrina dichotoma*, *Protaetia brevitarsis*, *Tenebrio molitor*, *Teleogryllus emma*, and *Gryllus bimaculatus* could be a good source of minerals, especially magnesium (82–304 mg/100 g dry weight) and zinc (10.26–22.43 mg/100 g dry weight). Zielinska et al. [41] analyzed the composition of some selected species: adult cricket (*Gryllodes sigillatus*), larvae of mealworm (*T. molitor*), and adult locust (*Schistocerca gregaria*) are very rich in copper (1.86–6.32 mg/100 g dry weight) and zinc (11.2–18.6 mg/100 g dry weight). Also, the calcium content of these species varies between 40 and 130 mg per 100 g of dry weight, while beef has on average 4–27 mg/100 g dry weight, pork 5–28, and poultry 5–14 mg/100 g [41].

Another compound is chitin, a complex polysaccharide commonly found in nature, particularly in crustaceans, fungal cell walls, and insect cuticles, which is the insoluble fiber (present in their exoskeleton) [42]. Edible insects can be considered as a potential source of dietary fiber in the human health due to their high content of chitin representing more than 10% (dry basis). For example, yellow-winged grasshoppers (*Arphia fallax*) and adult yellow mealworms (*Tenebrio molitor*) contain approximately 12% and 16% fiber in their composition (dry matter), respectively [28]. Also, the prebiotic properties of chitin derivative (chitosan) have been reported to benefit the immune system by slowing down the growth of some potentially pathogenic microorganisms [43]. Additionally, chitin and chitosan can be produced all year round and are available as a cheap byproduct with industrial insect rearing. However, commercial production of these components and the risk of allergic reactions have yet to be established and fully described.

Food legislation for edible insects' production and consumption

The production of insects as food for human consumption is generally at small-scale levels. In some tropical Southeast Asia countries such as Thailand, Vietnam, and Laos, crickets are mainly reared as food in backyard sheds with no need for expensive materials. However, to replace traditional animal sources, edible insects must be produced on an industrial scale [44]. The mealworms, wax moths, silkworms, crickets, and black soldier fly larvae are currently reared as food and are usually recommended as potential insect species for industrial-scale production because of their high oil and protein content and quality [45, 46].

In Europe, several companies and startups have been generated to commercialize insects as food for human consumption in the last decade. This framework rapidly created a regulatory response because of interest in commercial edible insects in the European market. The production and marketing of insects (Whole insects, their parts, and their derived ingredients) as food is governed by the 'Novel Foods' legislation—Regulation (EU) No 2015/2283 in the European Union (EU) [47–49]. According to current legislation, after the safety evaluation by the European Food Safety Agency (EFSA) [50–55] and a favorable vote given by the EU Member States (MS), the market authorization of these insect-based food products can be granted by European Commission (EC) [47]. There are currently four authorized species of edible insects as novel food in the EU. EFSA. Insects frozen, dried, and powdered for *Tenebrio molitor* larva (the yellow mealworm), *Locusta migratoria* (the migratory locust), *Acheta domesticus* (the house cricket), and *Alphitobius diaperinus* larvae (the lesser mealworm) [56–60]. However, comprehensive and systematic global research is needed to support and verify the favorable social and economic impact on the public of edible insect farming, primarily related to improving the future food security of low-income countries [8].

Edible insect consumer's concern: safety and acceptance

Eating insects is a widespread practice in many countries worldwide, especially in some specific tropical regions or in some ethnic communities [61]. However, accepting and adapting edible insects poses a primary challenge in the Western world. Several factors affect consumer reluctance to edible insect-based food products, for instance, its cultural unfamiliarity as a diet habit [26, 62], its association with health risk, and neophobia, which is the fear and rejection of trying new foods [47].

Even though consumers nowadays seem to be more open to novel food, disgust or yucky is still a core obstacle [63, 64]. Studies have shown that displaying a complete image of insects as a marketing strategy for insect-based food products in retail negatively affects consumers' willingness to purchase those specific food products [47, 65]. A strategy to minimize neophobia's psychological barriers and cultural aversions, the research has mainly focused on processing technologies, developing conventional food prototypes, and novel formulations for improving the sensorial properties of the final product and increasing consumer consumption [66]. One way to develop this product type is by using insect ingredients such as proteins, lipids, and vitamins. These ingredients could be isolated and incorporated into a product without visual changes [67]. Microbial contamination is one of the primary consumers' concerns about eating insects. Edible insects can be related to microorganisms in two ways: their internal microbiota (digestive system, cuticle, other anatomical parts) and external microbiome (rearing environment, nature). They can act as vectors for the spread of hazardous microorganisms, especially bacteria, and affect the total microbial load, safety, and shelf-life of food products they are processed [68]. Most studies have been focused on determining the bacterial biota in edible insects [69]. The most important food pathogens related to insects are *Staphylococcus aureus*, *Clostridium* spp., and species of the *Bacillus cereus* group [70]. There is still a lack of knowledge on the fungi, viruses, protozoa, and prion species associated with edible insects, as several food products such as fish, peanuts, eggs, crustaceans, and insects can also cause risks to consumers with allergies. Many diverse allergens are identified in edible insects, such as tropomyosin, arginine kinase, phospholipase, A fructose-bisphosphate aldolase, hyaluronidase, myosin light chain, α-tubulin, and β-tubulin [71, 72]. Tropomyosin, a protein complex found in the muscles of many invertebrate species such as crustaceans and insects, is considered a significant allergen [73]. Tropomyosin can cross-react with primarily other consumed foods like crustaceans or with common invertebrate inhalant allergens like house dust mites and their metabolites [74]. These allergens can induce non-specific symptoms, such as itching and flushed skin, eczema, urticaria, allergic asthma, hypotension, gastrointestinal symptoms, loss of consciousness, and tachycardia. Therefore, the allergic potential of edible insects should be observed to eliminate these risks, and edible insect-based food products must be labeled appropriately, not mislead consumers, and minimize allergic reactions [8, 25]. Even though the consumption of edible insects has been associated with some microbial, toxic, allergenic, and chemical risks, EFSA has established safety assessments for these novel food products to reduce these risks and published its positive opinions [49–55].

Can processing technologies affect edible insect-food products' safety and consumer acceptance?

As the production of edible insects expands on an industrial scale, the implementation of suitable post-harvest and processing technologies that can ensure the safety, preservation, quality enhancement, fractionation, and proper storage of insects and insect derivatives becomes essential [75].

After immediate harvesting, edible insects can be traditionally consumed as whole insects (raw or cooked). Also, they can be processed or transformed into non-recognizable and more palatable forms, like powder and paste. In addition, isolated proteins, lipids, or fiber (chitin) can be utilized as food ingredients to enhance existing food products such as bread, pasta, and biscuits or produce novel products such as oil, beverages, and confectioneries. Therefore, processing could contribute to their introduction to the daily human diet, especially for consumers in the Western world, and ensure safety [76].

Basic food processing techniques have often been applied to improve safety, increase shelf-life, and sensorial and nutritional quality. Principally, thermal techniques such as roasting, frying, boiling, blanching, drying, toasting, and steaming, followed by mechanical techniques such as grinding, milling, centrifuging, and sieving [77]. In the case of extraction and isolation of insect derivatives more novel processing novel technologies are applied (Fig. 1).

Safety and quality perspective

Microbial aspects

The prior condition associated with the thermal processing of edible insects is microbial and enzymatic inactivation [68]. Vandeweyer et al. [78] observed that blanching followed by microwave drying resulted in significant microbial reductions (total viable count, psychotropic aerobic count, Enterobacteriaceae, yeasts and molds, and lactic acid bacteria) regardless of treatment times (10, 20, 30, and 40 s). Nevertheless, aerobic bacterial endospores were more resistant to the treatments implemented than vegetative cells. Similarly, Wynants et al. [79] reported that the number of Enterobacteriaceae, lactic acid bacteria, and fungi dropped significantly, and there was a reduction in the total microbial count of 4.0 log cfu/g, but aerobic endospores persisted after blanching. Larouche et al. [80] compared different

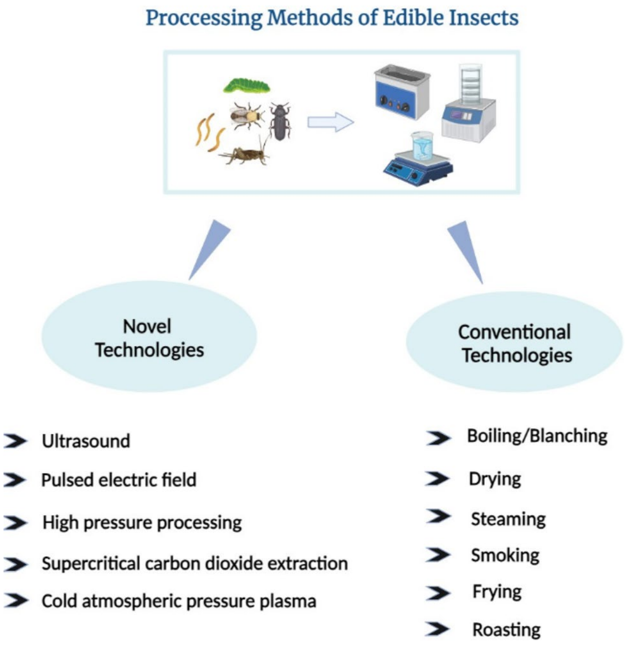

Fig. 1 Different processing methods applied to edible insects

processing methods for black soldier fly larvae, including blanching, freezing, desiccation, grinding, drowning using various gases (100% CO_2, 100% N_2, vacuum conditioning), and high hydrostatic pressure and found that blanching, achieved by boiling the larvae in water for 40 s, was the most effective method to reduce microbial load. The total microbial load of the *T. molitor* of 7.72 log10 cfu/g was reduced to 4.73 log10 cfu/g following cold atmospheric pressure plasma treatment for 15 min. In contrast, equally long thermal treatments at 120 and 140 °C were found to completely inactivate the native microorganism flora [81]. Boiling and toasting reduced *Staphylococcus aureus* by 4.8–6.4 log cycles and total viable counts by 4–6 log cycles and eliminated the yeasts and molds, Lac + enteric bacteria, and Salmonella [82]. Megido et al. [83] investigated the impact of boiling, frying, and under vacuum cooking on the microbial load of mealworms, showing a reduction of the total microbial load from 8.5 to 1.6, 3.3, and 3.9 log cfu/g, respectively.

Quality and nutritional aspects

The processing techniques may have different influences on the quality characteristics of insects. Freeze-drying and microwave-drying methods caused only minor changes in protein, fat, and ash content of the larvae, while microwave drying reduced the vitamin B_{12} content of the mealworms compared to freeze-dried samples, and the fat fraction of freeze-dried samples showed higher oxidation than the microwave-dried samples [84]. Furthermore, in all dried mealworm samples, the water activity was below 0.60 (for blanched plus freeze-dried and freeze-dried samples, the water activity was even below 0.30). Azzolini et al. [85] reported that blanching had no significant differences in proximate composition between fresh and blanched samples (dry matter). Kröncke et al. [86] showed that all drying methods tested (microwave-drying, freeze-drying, vacuum-drying, fluidized-bed drying, and conventional hot air drying) caused minor changes in protein, fat, and fiber content of the mealworms, freeze-dried mealworms showed significantly highest oxidation status than the other dried samples, while protein solubility was highest at freeze-drying. Megido et al. [83] compared several cooking techniques (boiling, vacuum cooking, frying, and oven cooking) for preparing mealworms and demonstrated that frying reduced protein content and digestibility, while boiling and cooking under vacuum increased polyunsaturated fatty acids. Singh et al. [87] observed no difference in lipid concentration in house cricket between blanching (40 s at 100 °C) and freezing (2 h 10 min at -20 °C). Although tested methods increased the browning index, they had no detrimental effects on product quality. The browning index of microwave-dried mealworms remained stable in contrast to that of freeze-dried during four months of storage [84]. The lightness and yellowness color values decreased when the insects were subjected to blanching + freeze-drying and blanching + air-drying treatments compared to fresh (or only) freeze-dried samples. However, there were no significant changes observed in redness (a∗). In terms of color preservation, oven-drying at 50 °C, followed by a blanching treatment, offered an economical approach compared to freeze-drying [85]. Blanching and microwave-assisted drying noted a dark color appearance, and the products were considered over-processed [78]. Fombong et al. [88] studied the impact of freeze-drying and oven-drying on the nutrient composition of blanched grasshoppers (*Ruspolia differens*). They found that both approaches showed the same nutritional quality (proximate, amino acid, mineral, and fatty acid compositions) and could be used to formulate food products containing insects without noticeable sensorial quality.

Khampakool et al. [89] pre-treated larvae with infrared before freeze-drying, and they found that lower hardness, chewiness, and higher protein content levels, and better-preserved glutamic acid (6.30–7.29 g/100 g) and proline (3.84–5.54 g/100 g) concentrations compared to non-pretreated freeze-dried and conventionally dried samples (oven). Additionally, the surface appearance of the dried larvae after the infrared-assisted freeze-drying technique showed more air pores and volume expansion compared to the hot air drying-derived product, which might result in a good consumer appeal for dried snack products.

Novel processing alternatives for edible insect derivatives

Besides using edible insect powders and their incorporation into a food product, different processing technologies (Table 1) have also been applied to produce insect-based ingredients such as protein, lipids, and fiber (chitin/chitosan). These derivatives are utilized to produce food analogs, fortified products, and as techno-functional ingredients in complex systems to enhance sensorial characteristics and stability of final products. In general, the derivatives can be used as foaming, gelling, thickening, structuring, and emulsifying agents [10, 66, 77, 90]. However, the processing might affect the structure of the compounds. Therefore, the selecting of appropriate methods for the preparation of derivatives with high functional and nutritional value is an essential step.

Proteins

The basic methodology for extracting globular proteins is alkaline solubilization, precipitation (acid or thermal), and ultrafiltration or dialysis to increase the purity. However, additional steps, such as defatting and assisted alternative

Table 1 Food processing technologies used to extract valuable compounds from various edible insects

Aim of the process	Insect species	Processing method	References
Protein extraction			
	A. domesticus	Aqueous extraction Hexane extraction	[91]
	T. molitor	Alkaline extraction	[92]
	T. molitor	Centrifugal fractionation	[93]
	L. migratoria	Alkaline extraction Mechanical chitin removal	[94]
	T. molitor	Dry fractionation	[95]
	S. gregaria *Apis mellifera*	Sonication-assisted extraction Alkaline extraction Defatting	[96]
	Coridius viduatus *Agonoscelis versicoloratus versicoloratus*	Acid extraction Alkaline extraction Water extraction	[97]
	A. domesticus	Pulsed electric fields Defatting Alkaline extraction	[98]
	T. molitor *G. bimaculatus* *B. mori*	Ultrasound-assisted extraction Defatting	[99]
Fat extraction			
	T. molitor *A. diaperinus* *A. domesticus* *Blaptica dubia*	Aqueous extraction Soxhlet extraction Folch extraction	[100]
	T. molitor	Defatting Ethanol extraction Methanol extraction	[92]
	T. molitor	Supercritical CO_2 extraction Hexane extraction	[101]
	Clanis bilineata	Ultrasound-assisted extraction Aqueous extraction Soxhlet extraction	[102]
	H. illucens	2-methyltetrahydrofuran extraction Hexane extraction	[103]
	H. illucens *Lucilia sericata* *T. molitor* *Zophoba morio* *L. migratoria* *A. domestica* *Anacridium aegyptium*	Direct methylation Direct saponification (KOH and ethanol) Direct methylation pure *n*-hexane Pure acetone Ethanol/water Hexane/ethanol	[104]
	T. molitor	Compressor	[105]
	A. domesticus *T. molitor*	Ultrasound-assisted extraction Pressurized liquid solvent extraction	[106]
	A. domesticus *T. molitor*	High hydrostatic pressure-assisted extraction Hexane extraction	[107]
Chitin extraction			
	Holotrichia parallela Motschulsky	Chemical extraction (demineralization, deproteinization, and decolorization)	[108]
	Pimelia sp.	Chemical extraction (demineralization, deproteinization, and decolorization)	[109]
	A. domesticus	Pulsed electric fields Chemical extraction (demineralization and deproteinization)	[98]

non-thermal techniques (ultrasound and HPP), are used to pretreat the starting material to increase the protein yield [103, 110]. It has been stated that both processing parameters and insect species (composition) can determine the protein characteristics (nutritional and functional) [92, 111].

The protein content in proteinaceous insect powders from grasshoppers (*Schistocerca gregaria*) and honeybees *(Apis mellifera*) increased after defatting (hexane) and sonication-assisted alkaline extraction [96]. The authors also indicated that protein-emulsifying properties were enhanced compared to whey proteins. Ndiritu et al. [91] concluded that hexane extraction recorded higher protein yield, color values (lightness and hue angle), crude protein content, and crude ash than aqueous extraction. Nevertheless, aqueous extraction showed better protein emulsifying and foaming capacities and stabilities than hexane extraction. Psarianos et al. [98] conducted a study on the impact of pulsed electric fields (PEF) on the extraction of the protein from cricket (*Acheta domesticus*) powder. They reported that this treatment (4.90 kJ/kg, 60 min) resulted in a significant increase in protein yield (~ 46 g protein/100 g dry matter) compared to the untreated one (~ 39 g protein/100 g dry matter), improved techno-functional properties by increasing oil binding and emulsifying capacity over 40% and 70%, respectively, did not affect water binding capacity and foaming capacity. Zhang et al. [112] applied ultrasound-assisted alkaline extraction using different times (10, 20, 30, 40, and 50 min) to obtain protein from *Tenebrio molitor* and observed that ultrasonication could effectively alter the structural properties of proteins (primarily secondary and tertiary structures, thermal stability) which might result in improved functional properties, and was the optimal ultrasound parameter 30 min.

Lipids

Although more conventional lipid extraction methodologies are carried out using organic solvents (hexane, ethanol, methanol, among others), mechanical pressing and novel technologies such as supercritical carbon dioxide have emerged as green and environmentally friendly alternatives [103, 110].

Tzompa-Sosa et al. [100] studied the chemical composition of lipids extracted from four insect species (*Tenebrio molitor*, *Alphitobius diaperinus*, *Acheta domesticus*, and *Blaptica dubia*) using various extraction methods and found that *T. molitor* contained the highest lipid content among the four insect species, the highest lipid yield was obtained via Folch extraction while aqueous extraction followed by centrifugation gave the lowest lipid yield, but the highest ω-3 fatty acids content and lowest ω-6/ω-3 fatty acids ratio. However, although the Folch procedure could be an effective method for lipid fractions characterization, it is not considered a food-grade recovering method (because of using chloroform as a solvent). Sun et al. [102] used ultrasound-assisted aqueous extraction and reported that oil had lower peroxide values, higher polyunsaturated fatty acids contents, and thermal stability and showed stronger antioxidant activities than Soxhlet extraction-derived oil samples. Another study using ultrasound-assisted extraction showed that higher lipids extraction from crickets and mealworms was found when pressurized liquid extraction was used compared to ultrasound-assisted extraction; however, using ultrasound improved the fatty acid profile (in terms of linoleic, oleic, and palmitic acids) of both insect species [106]. Purschke et al. [101] applied the supercritical carbon dioxide extraction method and effectively achieved the maximal oil extraction yield (95%) from mealworms at high pressure and moderate temperature (400/250 bar, 45 °C, and 105 min). Nevertheless, there was no significant difference in yield and oil composition when using hexane.

Chitin

Chitin and its deacetylated form, chitosan, have widely attracted attention thanks to their beneficial biological properties such as nontoxic, antimicrobial, antioxidant, biocompatible, biodegradable, and edible properties in the food industry [113]. Kaya et al. [109] extracted chitin and chitosan from exoskeletons of *Pimelia* spp. They concluded that both chitin and chitosan showed antimicrobial activity against the common food pathogen bacteria (*Listeria monocytogenes*) and yeast (*Candida albicans*) and, therefore, have the potential for use in food protection. Also, they suggested that both chitin and chitosan can be used to design potential oil-binding food supplements as their oil-binding properties are well documented. Chitin was extracted from the adult beetle (*Holotrichia Parallela Motschulsky*) and compared with the commercial α-chitin from shrimp by Liu et al. [108]. Results indicated that the extracted chitin from the H. parallela exhibited similar characteristics to the chitin obtained from shrimp and could be used as an alternative source of chitin. Psarianos et al. [98] studied the effect of pulsed electric fields on chitin extraction from cricket powder as a pre-treatment. They concluded that although chitin yield was not affected by the pulsed electric fields treatment, the morphology of chitin was affected by this treatment.

Application of edible insect derivatives

Functionality in food systems

Due to their technological properties (emulsifying, stabilizing, gelling, water, and oil absorption), insect derivatives such as proteins are used as fat replacers, structuring agents, binders, and extensors. These compounds are also used to (i) fortify food products for enhancing their nutritional quality (mainly through protein supplementation), (ii) develop products for special nutritional needs (such as gluten-free products, or (iii) improve their physicochemical and sensorial properties (Fig. 2) [10, 13, 66, 77]. Edible insects are mainly utilized for ingredient replacement, to increase the nutritional value, and for food product reformulation (Table 2).

Food analogous

During the last few years, the analogs sector has experienced growth in the market. Currently, food analogs commercially available in the market are meat and meat products (burgers, strips, patties, sausages, chunks, chicken-like blocks, nuggets, ground beef-like products and steaks), and milk and dairy analogs (soya bean milk, almond milk, coconut milk, cheese, yogurt) [126–129].

Meat analogs intend to imitate the taste, texture, appearance, and functionality of given meat products in different forms (grounds, emulsions, and crumbles) [129]. For this purpose, water, fats, oils, textured plant-based proteins (soy, pea, and wheat gluten), coloring and binding agents (gums, hydrocolloids, and enzymes), flavors, and spices are among the most utilized analog ingredients to mimic the structural, nutritional, and sensorial characteristics of original meat products. These products are available in Europe, mainly in Germany, The Netherlands, France, Italy, Sweden, and the United Kingdom. Therefore, the availability of these palatable and healthy products plays an important role in satisfying both vegetarian and meat product consumers' demands [126, 130].

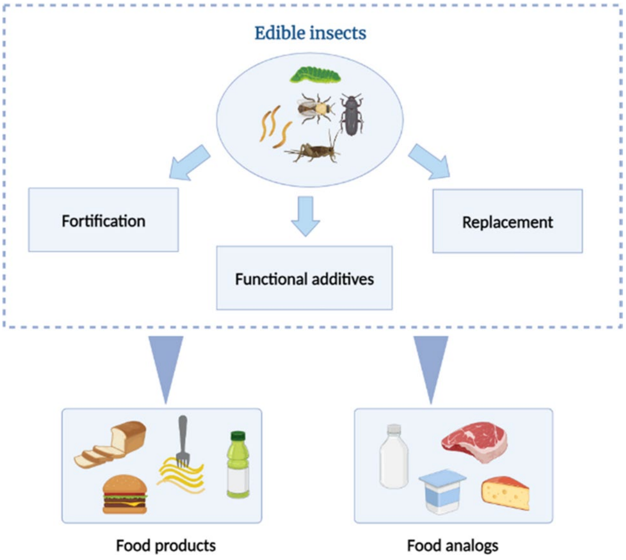

Fig. 2 Uses of edible insect derivatives

Several reasons pointed to the need to develop milk and dairy analogs, which include limited accessibility of milk in low-income regions, eating habits, religion, health issues related to protein allergy, lactose intolerance, and sustainability. The producers of milk and dairy analogs may use several additional ingredients to standardize their nutritional profile (lipids, proteins, sugars, and micronutrients mainly) and stabilize the product (hydrocolloids, lecithin) to approach similar properties of the original product. Usually, milk substitutes made from plant-based sources such as soybean, oats, rice, hemp, almond, and coconut are the most popular milk analogs in the market [127].

Cheese analogs, usually made by mixing given ingredients such as non-dairy fats, oils, or proteins to manufacture cheese-like products, offer nutritional benefits due to high unsaturated fatty acids, no cholesterol, and fewer calories. In addition, these products are considered cost-effective as cheaper vegetable products can replace the selected milk ingredients. Also, they have easier production compared with traditional cheese production. Cheese analogs, margarine, ice creams, and whipping creams are lower-cost and nutritionally advantageous alternatives [131, 132].

Even though the studies on insect-based food systems are increasing, mainly for meat products, other alternatives, such as milk and dairy products, have been less studied (Table 3) [22, 133, 134].

Cho and Ryu [138] investigated the effects of different *T.molitor* larva contents (0, 15, and 30%) and extrusion process parameters, including die temperature (140 and 150 °C) and moisture content (40% and 50%) using twin-screw extruder on the physicochemical properties of the extruded meat analog. Texture profile analysis and meat analog oxidation activity decreased with increased larva content, while water-holding capacity, protein digestibility, and antioxidant activity significantly increased. Lower die temperature and higher moisture content enhanced the textural properties but decreased protein digestibility. Azzolini et al. [137] studied different processing parameters ($CaCl_2$ concentration and processing temperature) to design insect-based-meat analog using protein from larvae of *Alphitobius diaperinus* and reported that around 74 g of coagulum could be obtained from 100 g fresh insects. The resulting product (at 100 °C, at 20 mmol of $CaCl_2$) demonstrated the desired texture and mouthfeel as the gelling properties of the insect proteins contributed to the formation of large protein aggregates and stranded structures.

Minced meat-like from mealworm larvae (*T. molitor* and *A. diaperinus*), insects were produced using different processing techniques (steam, stir, and pan-fried) and storage using air and modified atmosphere (MAP) packaging. The total aerobic count for fresh insect meat analogous (3.8

Table 2 Insect-based food products

Product	Insect species	Processing	Outcomes	References
Wheat bread	*H. illucens* *T. molitor* *A. domestica*	Freeze-drying Milling	Wheat flour replacement (5%) by three different insect powders reduced water absorption, increased the dough's stability, and improved the bread's protein and fiber content Bread containing 5% *A. domestica* powder showed similar volume and texture parameters to control samples	[114]
Pasta	*B. mori*	Commercial powder	10% insect powder addition increased the protein content from 26.2 to 30.3 g and obtained the highest overall acceptance compared to the control and 5%	[115]
Biscuit	*A. domesticus*	Commercial powder	5, 10, and 15% insect powder addition increased the biscuit's acidity, protein content, and dark color. The hardness was not affected Control and 5% substitution showed the best overall sensorial scores than 10 and 15%. Control and 5% substitution showed the best overall sensorial scores than 10 and 15%	[116]
Brown rice Cake	*Patanga succincta* L.	Freeze-drying Grinding Sieving Defatting	10, 20, and 30% replacement increased the protein content from 18.40, 20.83, and 24.94 g, respectively, compared to the control (14.94 g) Adding up to 20% insect powder provided desirable sensorial scores in 7–9 range)	[117]
Cake Cookie Waffle	*H. illucens*	Commercial insect fat	Butter replacement (25%) by insect fat did not change overall liking scores, and provided a similar structure and functionality to bakery products as butter	[118]
Muffin	*L. Migratoria* *T. Molitor*	Commercial flour Grinding	Fortification with both insect powders (15%) increased the protein, fat content, and baking yield. It decreased carbohydrate content, baking loss, and volume of muffins Samples containing both insect powders exhibited a softer texture than the control samples Adding *L. Migratoria* powder had adverse effects on sensory attributes by exhibiting darker color, denser structure, and lower volume than control and muffins with *T. Molitor* powder	[119]
Sausage	*Z. morio*	Commercial powder	Cooked samples (90 °C) with low insect contents (5 and 10%) showed similar viscoelastic properties but lower textural properties to standard samples Replacement of meat with insect powder positively affected cooking loss during heating and cold storage	[21]
Meat emulsion	*A. domesticus*	Commercial powder Spray-drying	10% replacement in meat emulsions increased protein content, and phosphorus, potassium, and magnesium minerals., and no negative effects on cooking yield, and textural properties	[120]
Meat batter	*B. mori*	Vacuum-drying Grinding	Meat batters formulated with insect powder (15%) exhibited significantly higher protein content and lower cooking loss than control samples, and no significant difference in redness value compared to the control	[121]
Frankfurter	*T. molitor*	Commercial insects Grinding	Control samples had the highest hardness, gumminess, and chewiness compared with all samples with insects Products with up to 10% insect were similar in cooking loss, emulsion stability, protein solubility, and overall acceptability compared to control products	[20]

Table 2 (continued)

Product	Insect species	Processing	Outcomes	References
Emulsion sausages	*T. molitor* *B. mori*	Freeze-drying Grinding Defatting Acid hydrolysis	10% replacement in meat emulsions increased cooking yield, and textural properties and had no impact on protein solubility of emulsion sausages	[122]
Ice cream	*C. viduatus* *A. versicoloratus versicoloratus*	Defatting Grinding Extraction (Acid/water/alkaline)	The developed ice cream products using the gelatin extracted from the two insects showed a significant difference regarding their taste and texture when compared with the commercial gelatin ice cream	[97]
Hummus Cracker	*T. molitor*	Commercial insect oil Deodorization	Both food products formulated by total and partial vegetable oil substitution using deodorized *T. molitor* oil showed good sensory attributes and the overall food experience scores compared to crude oil	[123]
Potato chips	*T. molitor*	Commercial insect oil Deodorization	Chips fried in the blend of vegetable oil + deodorized insect oil (50%/50%) was the most preferred sample compared with samples with crude oil. Consumer's sensory experience and preference of the products was similar for deodorized insect oil as traditional vegetable oil	[124]
Donut	*T. molitor*	Commercial insect oil Deodorization	Products fried in deodorized insect oil and in deodorized insect oil blended with vegetable oil (50%/50%) showed good overall acceptance scores compared to crude oil	[125]

log cfu/g) was lower than beef minced meat (4.9 log cfu/g), and after 28 days of storage, air-packed samples showed no microorganism growth [139]. Insect margarine was successfully formulated by replacing 75% oil plants with *H. illucens* and *T. molitor* lipids without adversely affecting spreading and color [133]. Some enterprising entrepreneurs may seek to start black soldier fly farms less for waste removal and more for production of the larvae, if not for livestock feed, then for high-protein and low-carb food to combat unhealthy diets, or for more creative cuisine such as EntoMilk™ (Cape Town, South Africa) [142]. Tello et al. [22] developed an insect-based milk analog using frozen *T. molitor* larvae. Although the resulting product is standardized with insect-extracted fat, ascorbic acid (as a preservative), and sunflower lecithin (as an emulsifier), it had low protein content (1.19%) compared to bovine milk (around 3.5%), the authors indicated this analog showed the flexibility of insects as a food source and underlined their potential for product development.

Conclusion

Edible insects are a promising sustainable source of ingredients for food product development for human consumption. Based on food security, sustainability, and nutritional quality in the food industry, insect-based food alternatives could contribute to the globally increased food demand. This review shows that bakery goods are the most studied insect-containing food systems, followed by meat products. In the case of food analogs, only meat prototypes have been extensively explored. More research should be conducted on other products, such as milk and dairy, representing an important niche market. Insect-based milk and dairy analogs (yogurt, ice cream, whipped cream, and cheese, among others) are nutritionally advantageous because they contain unsaturated fatty acids, protein quality, and are lactose free.

Table 3 Food analogs containing edible insects

Product	Ingredients	Insect species	Processing	References
Jerky analog	Textured vegetable protein (62.35% protein) Frozen mealworms Isolated soybean protein (2%) Transglutaminase (2%)	*T. molitor*	Grinding Homogenization Convection drying	[135]
Extruded meat analog	Soy protein concentrate (69% protein) Soy fiber *A. diaperinus* protein concentrate (68% protein content)	*A. diaperinus*	High-moisture extrusion	[136]
Meat analog	Frozen insects' larvae (15.2% protein) CaCl$_2$	*A. diaperinus*	Blending Heating protein precipitation (90 and 100 °C) Salt induced Protein coagulation (10–25 mmol/L)	[137]
Extruded meat analog	Defatted soy powder Isolated soy protein Corn starch Dehydrated mealworm larva	*T. molitor*	Extrusion cooking	[138]
Minced meat-like product	Pulverized larvae Spices	*T. molitor* *A. diaperinus*	Steaming Pan-frying Stir-frying	[139]
Milk analog	Frozen insects' larvae (20.1% protein) Sunflower lecithin Ascorbic acid	*T. molitor*	Grinding Supercritical CO$_2$ extraction Pulsed electric fields	[22]
Margarine	*H. illucens* insect fat *T. molitor insect* oil	*H. illucens* *T. molitor*	Supercritical CO$_2$ extraction	[133]
Emulsions	*Ascra cordifera* protein concentrate *Brachygastra mellifica* protein concentrate *H. illucens* protein concentrate Tricaprylin oil	*A. cordifera* *B. mellifica* *H. illucens*	Freeze-drying Grinding Alkaline extraction Hexane extraction	[61]
Emulsions	*T. molitor* protein powder	*T. molitor*	Freeze-drying Grinding Alkaline extraction Vacuum-drying	[140]
Nano-emulsions	*H. illucens* oil Hydrogenated lecithin D-α-tocopheryl polyethylene glycol 1000 succinate	*H. illucens*	Hexane extraction Degumming waxing Bleaching	[141]

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Declarations

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Research studies involving with humans and/or animals Not applicable.

Consent to participate Not applicable.

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