Comprehensive REVIEWS in Food Science and Food Safety

Edible Insects Processing: Traditional and Innovative Technologies

Guiomar Melgar-Lalanne, Alan-Javier Hernández-Álvarez, and Alejandro Salinas-Castro

Abstract: Insects are part of the human diet in many parts of the world. Their nutritional value is widely recognized. Currently, most edible insects are harvested from the wild, although semi-domestication and indoor farming have increased insect availability and the sustainability of production. In traditional cultures, insects are processed in a number of ways (steaming, roasting, smoking, frying, stewing, and curing, among others) to improve their sensory and nutritional qualities as well as their shelf-life. In order to increase consumer interest in the West, various technologies have been developed that are aimed primarily at using insects as ingredients in a non-recognizable form, such as powders or flour. These technologies include drying (sun-drying, freeze-drying, oven-drying, fluidized bed drying, and microwave-drying) and new processing methods (ultrasound-assisted extraction, cold atmospheric pressure plasma, and dry fractionation) designed mainly for protein, fat, and/or chitin extraction. Insect-based ingredients are sold for the production of cookies, chocolates, tortilla-style chips, and other snacks. This review focuses on edible insect production, processing technologies, and commercialization using strategies ranging from traditional to novel as a sustainable approach for improving food security worldwide.

Keywords: cooking, edible insects, food processing technologies, insect farming, neophobia, review

Introduction

Nearly 2.5 billion people in the world currently supplement their diet with insects (Van Huis, 2016). Edible insects are mostly consumed in tropical regions, which have high levels of biodiversity, suggesting that ecological factors related to the abundance of insect species have influenced consumption patterns (Lesnik, 2017). In most parts of Europe, and among non-aboriginal Americans, Canadians, Australians, and New Zealanders, entomophagy remains rare or even a taboo (Shelomi, 2015). Whereas in the Western World, people tend to associate insects with plagues and health risks, in tropical countries, they are part of culinary traditions, mostly in rural areas. People in many parts of Asia, Africa, and Latin America consume whole insects in a perfectly recognizable form, either as snacks or as part of their daily diet. Insects are usually boiled and dried, toasted, or fried before being incorporated into different dishes.

Despite the high nutritional quality of edible insects, concerns have been raised about the lack of sanitary and quality controls applied in connection with their sale. Insects are typically sold in bulk, a situation that has worried public health officials with responsibility for food safety (Belluco et al., 2013; UN, 2015). Such concerns are based on a wide variety of studies that have been conducted on the prevention of food-borne diseases (microbiological, allergenic, and chemical; van der Fels-Klerx, Camenzuli, Belluco, Meijer, & Ricci, 2018). The lack of hygiene and inadequate processing and storage conditions are viewed as a more significant concern than the quality of the insects themselves, as they are not usually toxic to humans. It is crucial to implement appropriate post-harvesting technologies for the conservation, transformation, distribution, and storage of edible insects, in order to provide products that are safe and wholesome, thereby reducing consumers' fears.

Edible insects are considered the main solution to the problem of how to meet the growing global demand for animal protein that is sought after for its high nutritional value (Bruinsma, 2003). Although edible insects generally have a high nutritional value, nutrient composition varies with the species, life stage, sex, and diet. The nutritional value of edible insects is widely recognized (Ayensu, Annan, Edusei, & Lutterodt, 2019; Elhassan et al., 2019; Feng et al., 2017; Rumpold & Schlüter, 2013). In Figure 1, a short summary of the nutritional content of the nine insect orders is provided. Most of the species analyzed belonged to the order Orthoptera (grasshoppers, locusts, and crickets) and Lepidoptera (caterpillar). The least represented orders were Odonata (dragonflies) and Blattodea (cockroaches). Insects are rich in protein (35.34 g/100 g dry weight (dw) for termites to 61.32 g/100 g dw for grasshoppers) and lipids (13.41 g/100 g dw for grasshoppers to 33.40 g/100 g dw for beetles). The lipid fraction is of high quality, being rich in mono- and polyunsaturated fatty acids, with a high omega 3: omega 6 ($\acute{\omega}$-3/$\acute{\omega}$-6) ratio (Zielińska, Baraniak,

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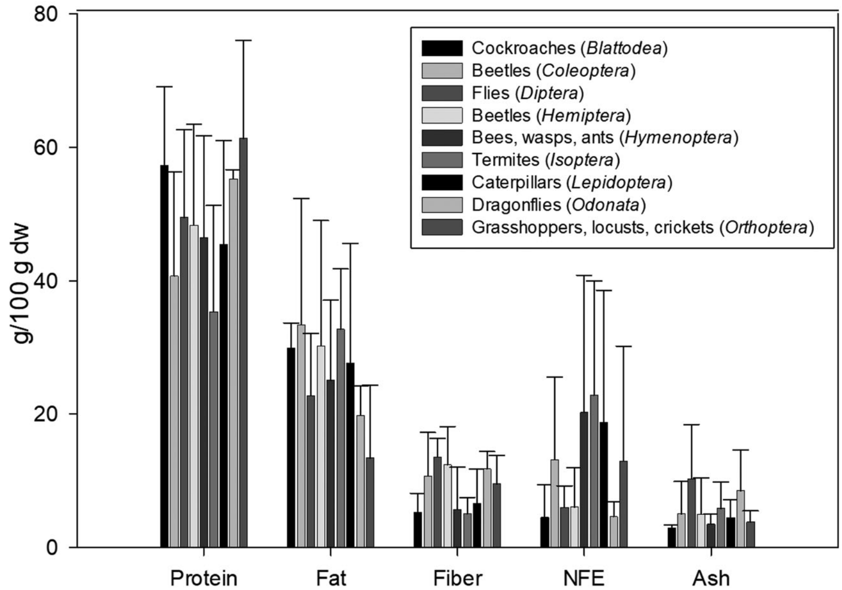

Figure 1–Nutritional composition of edible insect orders (1 g/100 g dry matter (*adapted from* Rumpold & Schlüter, 2013). NFE, nitrogen-free extract; number of species considered by order: *Blattodea*: 3, *Coleoptera*: 45, *Diptera*: 6, *Hemiptera*: 27, *Hymenoptera*: 45, *Isoptera*: 7, *Lepidoptera*: 50, *Odonata*: 2, *Orthoptera*: 51.

Karaś, Rybczyńska, & Jakubczyk, 2015). Insects also have a high chitin content, which ranges from 11.6 to 137.2 mg/kg in commercially raised insects (Finke, 2007). Given their low methane production, insects can play a key role in the fight against global warming (Van Huis & Dunkel, 2017). Unless food policies and eating habits change, the global food crisis could reach unprecedented levels with consequent risks to worldwide food security (Spiegel, Noordam, & van der Fels-Klerx, 2013). However, as mentioned earlier, insect consumption in the West is limited by the lack of industrialization strategies and by food neophobia.

A number of production and storage strategies have been developed to improve processing technologies. There is growing interest among entrepreneurs in semi-domestication of insects in the wild and indoor farming (Varelas & Langton, 2017). Unfortunately, to date, only a few species can be considered fully domesticated, including bees, silkworms, and cochineals, while termites, flour worms, and crickets are considered semi-domesticated (Vantomme, 2015). Various technologies can be used: traditional sun-drying (Manditsera, Lakemond, Fogliano, Zvidzai, & Luning, 2018), microwave processing (Vandeweyer, Lenaerts, Callens, & Van Campenhout, 2017), freeze-drying, oven-drying (Fombong, Van Der Borght, & Vanden Broeck, 2017), dry fractionation (Purschke, Brüggen, Scheibelberger, & Jäger, 2018a), freezing (Melis et al., 2018), marination, and fermentation (Borremans, Lenaerts, Crauwels, Lievens, & Van Campenhout, 2018). In addition, several modified atmosphere packaging methods have been explored to increase the shelf-life of these products (Stoops et al., 2017). Also, various "disguised insect products" have been successfully formulated, such as chocolates, cookies, and ground beef, among others (Azzollini, Derossi, Fogliano, Lakemond, & Severini, 2018; Homann, Ayieko, Konyole, & Roos, 2017; Walia, Kapoor, & Farber, 2018).

In general, eating behavior is influenced by the social context and shaped largely during early childhood (Higgs & Thomas, 2016; Scaglioni et al., 2018). In Western countries, women are more reluctant than men to eat insects, particularly in whole and perfectly recognizable forms (Sogari, Menozzi, & Mora, 2019; Verbeke, 2015), while young adults, especially those with higher levels of education, are the most likely to be willing to try insect-based foods (Hartmann, Shi, Giusto, & Siegrist, 2015). Although changes in food choices are difficult to predict, a number of other new foods have achieved acceptance over the years, such as sushi, quinoa, and kale. Other recent introductions to the market include kefir, kombucha tea, and goji berries, which were completely unknown to consumers in the West just a few years ago (Shelomi, 2015).

In some European countries, consumers have shown an interest in new food products that use insects as ingredients in an unrecognizable form (Figure 2). For example, if insects are used in flours or powder, or are added to different products, such as energy drinks, cookies, and corn tortillas, consumers, particularly young people, are more likely to accept them (Hartmann & Siegrist 2016; Hartmann & Siegrist 2018). This is a promising market niche that should be targeted through the development of food technologies and innovations.

Another area of interest consists of the development of functional ingredients for food, feed, pharmaceutical, and industrial applications. Ingredients of interest such as chitin (Song et al., 2018), oleic acid (Purschke, Stegmann, Schreiner, & Jäger, 2017; Sun et al., 2018), proteins (Bußler, Rumpold, Jander, Rawel, & Schlüter, 2016; Huang et al., 2018; Ndiritu, Kinyuru, Kenji, & Gichuhi, 2017), and bioactive peptides (Montowska, Kowalczewski, Rybicka, & Fornal, 2019; Nongonierma & FitzGerald, 2017; Zielińska, Karaś, & Jakubczyk, 2017) have been partially or totally extracted and purified. Nonetheless, scaling up these processes to the industrial level would still be too costly (Lamsal, Wang, Pinsirodom, & Dossey, 2019).

In summary, the production, processing, and storage of edible insects are achieved using a variety of approaches ranging from conventional to innovative. Food neophobia, sustainability, and convenience have a significant influence on the introduction of insect products to the market (Dobermann, Swift, & Field,

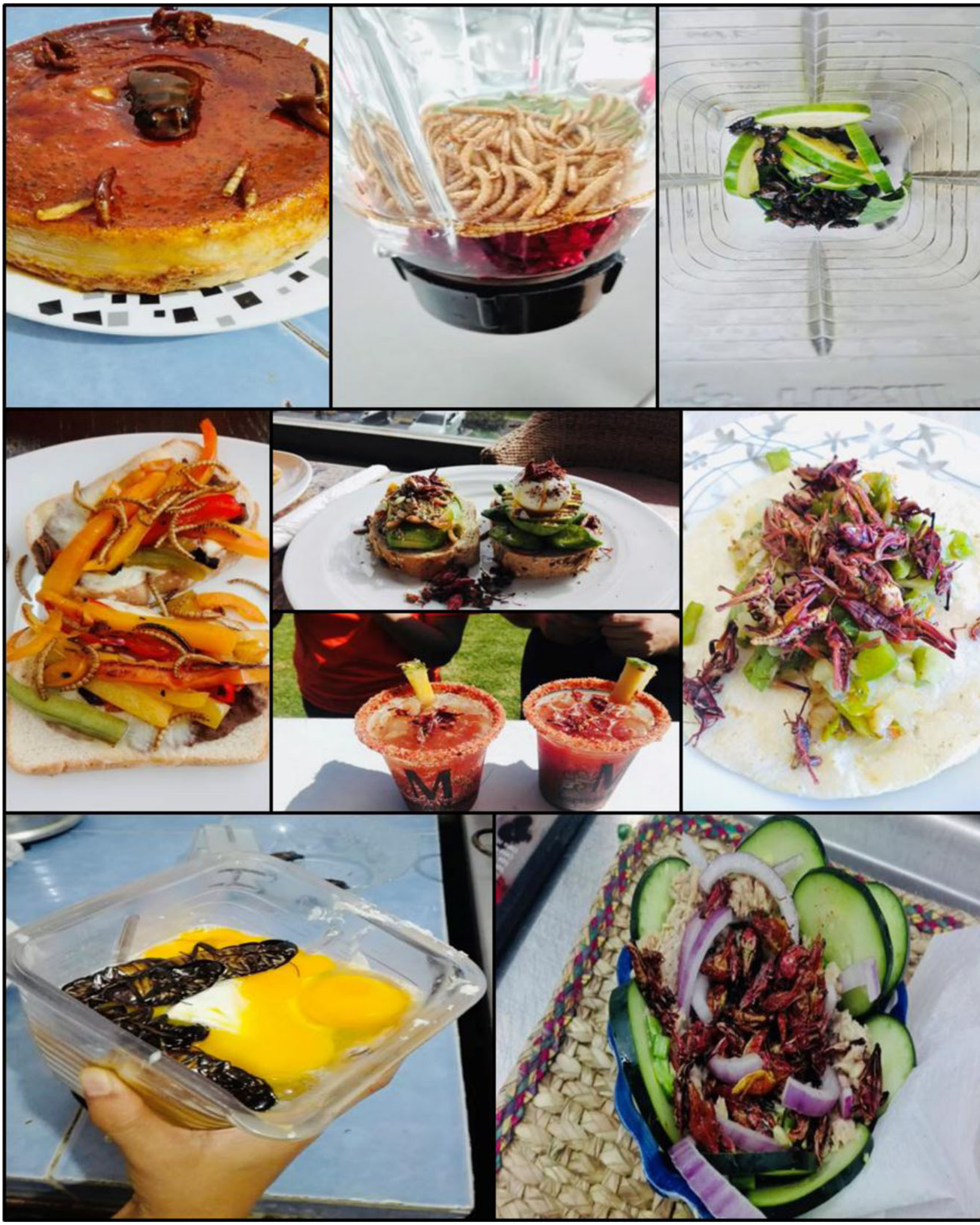

Figure 2–Some edible insect food preparations (*courtesy of Chef Mario Melgarejo Piñón*).

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Food Neophobia and Aversion to Insect Consumption

The development of taste starts *in utero* and it is shaped, at the most basic level, by biological factors, including an innate preference for sweet foods and an innate aversion to bitter and sour flavors (Ventura & Worobey, 2013). These preferences can change over time with repeated exposure and pragmatic learning through complex social, cultural, and even religious systems, depending on factors such as age, gender, health status, education, and income level (Giordano, Clodoveo, De Gennaro, & Corbo, 2018). Although food taste preferences are related to the flavor of foods, they are also viewed as the set of preferences and/or aversions associated with emotional and cultural states (Wright, Nancarrow, & Kwok, 2001). Food taste preferences reflect a spectrum of attitudes, from neophobia, fear of tasting new food, to neophilia, just as curiosity about and the desire to try novel food sources. Neophobia is strongly associated with fear of the unknown for sanitary, cultural, or even religious reasons (Giordano et al., 2018; Hartmann & Siegrist, 2018), and neophilia is associated with the development of cuisine, which allows the incorporation of new food items into the diet to satisfy the need for variety (Armelagos, 2014).

Neophobia is closely related to the emotion of disgust. Disgust, a primary emotion related to sensory qualities, such as appearance, taste, and aroma, is determined by the implicit association that people have with the disgust-eliciting object. Disgust is more difficult to eliminate than neophobia. However, both neophobia and disgust contribute to individuals' unwillingness to include a specific food in their daily diet (La Barbera, Verneau, Amato, & Grunert, 2018). Judging from the findings of blindfolded sensory taste experiments in which participants had difficulty identifying edible insect products (Meyer-Rochow & Hakko, 2018), sight may have a more significant influence on disgust toward insects.

The positive attitude needed to overcome food neophobia implies an interest in novel foods and enjoyment of a wide variety of foods, even unfamiliar ones. This positive attitude may be related to the strength and characteristics of each food culture. Some studies blame culinary maturity in Western cultures for their negative attitude toward consuming insects (Piha, Pohjanheimo, Lähteenmäki-Uutela, Křečková, & Otterbring, 2018). However, this point is not clear enough. Willingness to try novel foods has been found to vary from country to country. Swedes are more willing to do so than Americans and Finns, and Koreans are more reluctant than Americans (Dimitrovski & Crespi-Vallbona, 2017).

Some studies have shown that North Americans and Europeans are willing to eat insects if they are in an unrecognizable form. Therefore, processing methods may promote consumption in the future. In practice, dried insects may be crushed or pulverized, and raw or boiled insects can be ground or mashed, making them unrecognizable (Menozzi, Sogari, Veneziani, Simoni, & Mora, 2017; Mlcek, Borlovcova, Rop, & Bednarova, 2018).

There are many ways in which insects are associated with recreational activities and tourism and become part of culinary experiences (Perdue, 2018). The tourism experience involves eating insects as part of "ecotourism vacations," with the ultimate aim of maintaining the biodiversity of native ecosystems. This is the case for tourism excursions to the headwaters of the Amazon in Ecuador, Ariau in Brazil, Tado in Indonesia, and the bush-tucker experience with Australian Aborigines. In Kenya, the International Centre of Insect Physiology and Ecology is a pioneer in implementing "ecotourism mechanisms" involving the sustainable use of natural forest products, including commercial insects. However, the long-term impact of these experiences has not been sufficiently explored (Yen, Hanboonsong, & Van Huis, 2012).

Tourism, recommendations from close relatives or friends, and increasing media attention may encourage insect consumption, mostly by early-adopters (Sogari, Menozzi, & Mora, 2017; Van Thielen et al., 2018). Culinary tourism could help introduce people to new foods, since tourists are usually more motivated to change their habits and willing to try something unusual during their vacations (Dimitrovski & Crespi-Vallbona, 2017). When tourists return home, they may have a positive influence on people close to them by increasing familiarity and allaying concerns (Barsics et al., 2017). In regions with a long history of entomophagy, many food festivals are held, targeting domestic tourists; therefore, consumption is related with many different factors as tradition, identity and nostalgia (Sun-Waterhouse et al., 2016). In Thailand, the number of visitors to cricket farms, ethnic restaurants, and traditional markets has risen in recent years (Halloran, Roos, Flore, & Hanboonsong, 2016). Interest in eating insects is also increasing in countries without this legacy. For example, the North Carolina Museum of Natural Sciences holds an annual "Bug-Fest," which is attended by more than 35,000 people who "taste delectable dishes featuring creepy crawlers" as a major ingredient at "Café Insecta" (Perdue, 2018). In summary, culinary tourism is a useful avenue for exploring the multiple dimensions of entomophagy. Eating insects can be considered a novel strategy with positive ethical implications for addressing global warming but also, is an important way to recognize the tradition and culture in many parts of the world (Perdue, 2018).

Gender, age, health status, and income are other important factors that affect preferences with respect to trying edible insects. Gender influences preferences related to the visual appearance of insect-based products, with women being more traditional in their choices than men, and therefore more reluctant to try these types of products (Caparros Megido et al., 2016). Younger males show a more open attitude than women to including insects in their diets as a meat substitute in keeping with their concerns about the environmental impact of their food choices (Verbeke, 2015).

In order for insect-based foods to be adopted in the West, they must taste good, be attractive to consumers, and be readily available (Hartmann & Siegrist, 2016; Tan, Verbaan, & Stieger, 2017). Strategies like ethnic food markets and festivals have been developed to allow early-adopters to try whole, recognizable insects. Other strategies consist of promoting insects as an alternative to nuts and chips, since these snack foods have similar characteristics such as texture, macronutrient content, and flavor (Shelomi, 2015).

Approaches for using edible insects in familiar foods (e.g., incorporation into burgers, cookies, or chips) as a transitional phase in which minced or powdered insects are incorporated into common ready-to-eat preparations in small amounts have also been tried (Van Thielen et al., 2018). Processed foods, such as cookies or chips, containing only a small amount of insect flour are better accepted by consumers and allow them to become familiar with edible insects (Caparros Megido et al., 2017; Hartmann & Siegrist, 2016). Nevertheless, the use of familiar preparations has not always led to the acceptability of the final prepared product because consumers usually expect the insect preparations to have a taste that is inferior to that of the original products, even if they are visually

Table 1–Number of edible insect species consumed, in order of importance and by biogeographical region (*adapted from* Jongema, 2017).

Order	Common name	Afr.	Au.	Neartic	Neotrop.	Or.	Pal.
Araneae	Spiders	4	2	0	4	8	0
Coleoptera	Beetles	89	29	18	215	282	84
Dermaptera	Earwigs	0	0	0	0	1	
Dictyoptera	Cockroaches, termites and mantids	4	3	0	6	18	12
Diptera	Flies	5	1	15	12	3	6
Ephemeroptera	Mayflies	2	2	0	2	3	3
Hemitera heteroptera	True bugs	17	4	0	46	54	14
Hemitera homoptera	Cicadas	27	12	12	20	30	26
Hymenoptera	Ants, Bees, Wasps and Sawflies	32	14	23	224	42	51
Isoptera	Termites	34	1	1	18	17	16
Ixodida	Ticks	1	0	0	0	0	0
Lepdidoptera	Butterflies and moths	146	28	11	108	23	93
Megaloptera	Alderflies, Fishflies, Dobsonflies	0	0	0	2	0	2
Odonata	Dragonflies	3	2	1	15	34	7
Orthoptera	Grasshoppers	107	7	14	72	95	33
Phasmida	Ghost insects	0	2	0	1	4	0
Plecoptera	Stoneflies	0	0	2	0	2	5
Phthiraptera	Lice	0	0	0	3	1	0
Psocoptera	Bark flies	0	0	0	1	0	0
Trichoptera	Caddisflies	0	0	0	5	1	4
Total of species		**471**	**107**	**97**	**754**	**618**	**356**

Biogeographical regions: Afr.: Tropical Africa, Au: Australia; Neotrop.: Neotropics; Or.: Orient.; Nearctic: Nearctic; Pal: Palearctic.

identical. Preconceptions about the taste of a food tend to be more negative when the individual has never tasted the food before (Tan et al., 2017; Woolf, Zhu, Emory, Zhao, & Liu, 2019). Perceptions differ between novel and common foods, and the development of new products requires the selection of the appropriate type of products and adjustment of their properties to match consumer motivations compared with taste expectations (Tan et al., 2017). Good product development is crucial, and includes making the products more attractive to consumers and encouraging repeated consumption through incentives (Hartmann & Siegrist, 2016; Tan et al., 2017).

Even when insects are consumed as "invisible" ingredients, consumers must have a reason to choose the insect-based product so that they will consume it on a regular basis. Reasons for such choices relate more to factors such as visual appearance, taste, good value, and availability than to environmental sustainability or protein quality (House, 2016). Market availability of the products (whole or processed) and type of communication with consumers are primary factors in increasing the acceptance and consumption of insects in Western countries (Sogari et al., 2017). However, introducing insect products may require promotional efforts that go beyond messages related to the positive environmental impact and nutritional value of edible insects. This could include official and mass media recommendations aimed at facilitating the interaction between consumers and insect foodstuffs (Alemu, Olsen, Vedel, Pambo, & Owino, 2017). Other strategies, such as food festivals and ethnic festivals, could promote entomophagy by reducing the attendees' fear of tasting these types of products (Aguanta, 2018; Barsics et al., 2017).

Traditional consumer countries are grappling with their own complex neophobia issues owing to the fact that neophagia is associated with a perception of poverty. The problem is even more pronounced in urban areas, and some African countries, including Zimbabwe, Nigeria, and Botswana, have reported that young people are rejecting entomophagy (Ebenebe & Okpoko, 2015; Manditsera et al., 2018; Obopile & Seeletso, 2013). Although, in the West, edible insects are being promoted as an environmentally sustainable protein source to young people in higher income brackets, young people in countries where entomophagy is a traditional practice still perceive insect consumption as a source of shame and as being related to poverty and a provincial mindset. This contradiction is evident in countries like Mexico where insect markets, restaurants, and ethnic festivals have become increasingly popular among high- and middle-class tourist populations in urban areas, while consumption, harvesting, and farming are declining in rural areas associated with poverty. Despite the growing demand for edible insects in urban areas, production through wild harvesting and indoor farming is still limited, because farmers associate insects with poverty and do not view it as a potential source of income (Ramos-Elourdy, Pino-Moreno, & Martínez-Camacho, 2012).

To increase the inclusion of insects in daily diets, a successful strategy to consider involves serving snacks between meals. These types of snacks are increasing in popularity in the global market and are attractive to early adopters (Shelomi, 2015; Tan et al., 2017).

Farming Edible Insects

The growing demand for edible insects has created a challenge, namely the production of more edible insects in an economically efficient, safe, and sustainable manner (Gahukar, 2011). The lack of availability creates accessibility issues, and therefore, reduces opportunities for increasing trade (Shelomi, 2015). These two factors point up the need to make the technological leap from wild harvesting to indoor farming. In this sense, traditional indigenous knowledge associated with wild harvesting and local insect consumption can complement the scientific knowledge required to boost the supply of insects through large-scale farming (Raheem et al., 2018).

Harvesting from the wild (forests, waterways, or agricultural fields) is the most traditional way to gather insects. A large variety of species at various life stages can be collected, in keeping with the traditional and cultural practices of small-scale producers (Van Huis & Oonincx, 2017). These producers have the necessary expertise to recognize the proper timing, conditions, and host vegetation in order to produce specific edible species without damaging the environment (Durst & Hanboonsong, 2015). Insects are collected from fields mainly for home consumption, a practice that has a low environmental impact and helps maintain insect resources at a fairly constant level over time. Traditional harvesting has been carried out in Mexico since pre-Hispanic times when insects were not considered pests, but rather an important food source (Cerritos & Klewer, 2015), and more than 400 insect species were harvested from the wild (Cerritos & Cano-Santana, 2008), mostly from terrestrial ecosystems. The harvesting of each species is unique and depends on the stage of development (eggs, pupae, larvae, or adults), season (rain or dry), and location (forest, desert, or agricultural fields). Pupae of the ant species *Limetopum apicuatum* (*escamoles*) are collected during the warm dry season (February to May) and the eggs are removed from the anthills (Lara-Juárez, Rivera, Lara, & Reyes-Agüero, 2018); red maguey worms (*Hypopta agavis*) are picked from the pineapples of the maguey (*Agave saliminara*) after the start of the rainy season (Juárez-Ortega, Viesca-González, & Barrera-García, 2012); and grasshoppers belonging to the species *Sphenarium purpurascens* (*chapulines*) are manually harvested from fields when the rainy season starts (Cerritos & Cano-Santana, 2008).

Agricultural intensification poses a threat to many edible insects, primarily as a result of mechanization, tree clearance, and pesticide use. Pesticides have caused a decline in insect populations worldwide, with a 67% decline in invertebrate populations in the last 40 years (Payne & Van Itterbeeck, 2017). If agrochemical controls were eliminated, the potential yield of a specific grasshopper species in Mexico would generate an estimated annual income of nearly US$350,000 and would provide enough protein to feed close to 9 million people annually (Cerritos-Flores, Ponce-Reyes, & Rojas-García, 2014).

Uncontrolled overharvesting is causing ecological damage due to changes in the trophic chain (Gahukar, 2016; Van Huis & Oonincx, 2017). The increased demand for a few insect species has led to more aggressive harvesting techniques, without appropriate care being exercised to ensure sustainable collection during reproductive periods—a practice that could reduce or even eliminate local biodiversity (Durst & Hanboonsong, 2015; Van Huis & Oonincx, 2017). For example, the overexploitation of honey ants and wood grubs in Australia linked to demand from restaurants and ecotourism threatens their availability (Yen, 2009). Similarly, in the state of Hidalgo, Mexico, 18 edible insect species have been reported to be at risk of extinction due to overharvesting, habitat changes and pollution (Ramos-Elourdy, 2006). The development of sustainable techniques could reduce or even avoid the use of pesticides in agriculture that would have a positive impact on the environment (Cerritos & Cano-Santana, 2008; Van Huis & Oonincx, 2017). The long-term damage that overharvesting causes to the environment and native insect populations is still unknown. Efforts should be focused on prohibiting harvesting during breeding periods and using less destructive harvesting techniques (Durst & Hanboonsong, 2015).

The environmental and health risks have prompted an increase in the semi-domestication of some edible wild insect species in a more sustainable, less time consuming, and more consistent manner, mostly in traditional consumer countries where the warm, wet weather is appropriate for farming (Varelas & Langton, 2017). Semi-domesticated populations are those whose morphological, behavioral, physiological, and/or life-history traits result from human management actions, which involve partial control over breeding, mortality, space use, and food supply designed to increase potential economic profit (Mysterud, 2010). Outdoor farming includes rearing insects in old trees, sawdust, and forest wastes that, in addition to providing a semi-confined habitat, can be a source of food. In Thailand, bamboo caterpillars mate in nylon net cages placed over growing bamboo shoots. In addition, people in some areas of Thailand collect young wasp nests and protect them until they are ready to eat. Bamboo caterpillars are generally packed in plastic boxes and sold in local markets (Durst & Hanboonsong, 2015). In Africa and Asia, semi-domesticated bees are reared in wooden hives, old tree trunks, or other containers (DeFoliart, 1997). Similarly, in Manchuria (China), silkworms have been semi-domesticated to produce silk as well as food and feed with optimal stocking, to prune trees to control crown development and promote leaf flushing, and to produce fertilizer for legumes (Xiang et al., 2010). Weaver ants construct nests by weaving leaves together using larval silk. Some farmers in Thailand maintain colonies in host trees; the ants are harvested once a year (Hanboonsong, Jamjanya, & Durst, 2013) and used for medicinal and culinary purposes.

Domestication of edible insects is relatively simple and economical, although nowadays only three species are considered fully domesticated: bees, silkworms, and cochineals; several other species are partly domesticated. The main reasons for this are: (1) most insects can be easily reared in small spaces or containers; (2) their life cycle is short; (3) they can eat forest or agricultural wastes instead of grains; (4) insect farming can be carried out in both urban and rural areas; and (5) short-term financial returns are possible. House crickets and yellow mealworms are the most widely farmed insects in the world due to their commercial success; however, they are mostly sold as pet food (Gahukar, 2016). Most farmed insects can be easily raised in small ventilated plastic containers at high ambient temperatures (up to 30 °C) and relative humidity (up to 70%) and are fed organic wastes and cereals. They have low technical requirements, high production densities, and do not require sunlight during some life stages (Hanboonsong et al., 2013). The most commonly farmed insect is *T. molitor* L. In a recent review, Soares-Araújo, dos Santos Benfica, Ferraz, and Moreira Santos (2019) concluded that the optimal rearing temperature was 25 to 28 °C with relative humidity close to 70%, and the diet must contain 5% to 10% yeast, 80% to 85% carbohydrates, and B complex. There are many different strategies for feeding insects, including the use of food by-products and organic wastes. However, a diet with high protein (around 20%) and high fat (around 9%) contents is required to obtain the best results in terms of feed conversion efficiency, survival, development time, and nutritional composition. Bran or other by-products can be used as complements in the diet (Oonincx, van Broekhoven, van Huis, & van Loon, 2015). Vegetables and fruits in the diet are considered only as a water source, and a small quantity of water is added to prevent fungal contamination (Oonincx et al., 2015; Ramos-Elourdy, 2006; Soares-Araújo et al., 2019).

In Thailand, cricket farming was introduced in 1997, and crickets are currently sold directly to consumers and to other farmers at local and urban markets. Some producers are grouped in cooperatives and are recognized as important contributors to the rural economy and employment. Species preferred by consumers have been selected for indoor farming (Halloran et al., 2016).

Traditional Cooking

Studies have shown that traditional insect consumption is higher at lower latitudes, that is, in tropical regions of the world (see Table 1). Around the world, insects are consumed in 11 European countries, 14 countries in Oceania, 23 American countries, 29 Asian countries, and 35 African countries. Mexico, China, Thailand, and India are the leading consumer countries in the world and those with the most species described as Table 1 shows (Jongema, 2017).

Table 2–Blanching treatments usually applied to edible insects.

Insect species	Blanching treatment	Main findings	Reference
Alphitobius diaperinus (beetle)	Submerged in bath with water at 90 °C until water temperature reaches 88 °C (5 min).	Reduction in total microbial count of 4.0 log cfu/g but aerobic endospores persisted. No typical pathogens were identified. Some mold producers of mycotoxins found.	Wynants et al., 2018
Ruspolia differens (grasshopper)	Submerged in boiling water for 5 min, drained, and allowed to cool.	Not indicated.	Fombong et al., 2017
Tenebrio molitor L. (mealworm larvae)	Submerged for 10 min in boiling water in a 1/12 (w/w) larvae-water ratio.	Slight increase in water content but no significant changes in composition of macronutrients.	Purchke et al., 2017
Tenebrio molitor L. (live larvae)	Submerged for 1 min in boiling water or sterilized in cans with brine solution (5% NaCl) for 16 min at 120 °C.	Reduction in TVC (with boiling 4 log cfu/g) and sterilization (5 log cfu/g); No yeast or mold observed with either treatment.	Caparros Megido et al., 2017
Archea domesticus (house cricket)	Submerged in boiling water for 4 min or sterilized in cans with brine solution (NaCl 5%) for 16 min at 120 °C.	Reduction in TVC with boiling (4 log cfu/g) and sterilization (5 log cfu/g); No yeast or mold observed with either treatment.	Caparros Megido et al., 2017
Macrotermes spp. (smoked termites)	Submerged in boiling water for 1 min.	Reduction in TVC (3 log cfu/g) with boiling. No yeast or mold observed with either treatment.	Caparros Megido et al., 2017
Cirina gorda (mickwater caterpillar)	Submerged in boiling water for 5 min.	Reduction in TVC (3 log cfu/g). No yeast or mold observed with either treatment.	Caparros Megido et al., 2017
Tenebrio molitor L. (mealworm)	Submerged in boiling water for 3 min in a 1/10 (w/w) larvae-water ratio. Drained for 2 min, and excess water removed with absorbent paper.	Increase in water content. No significant changes in composition of macronutrients. Decrease in luminosity color factor. No microbiological data.	Azzollini et al., 2016
Tenebrio molitor (mealworm larvae)	a) Submerged in boiled water: - 1 min - 10 min - 5 min followed by oven-drying at 55 °C, 24 hr - 1 min in acid water (pH 4.0) b) Roasting for 10 min whole and crushed.	No significant differences in TVC, Ent, or BS were found with different boiling treatments. With roasting, more Ent were detected both in whole and crushed forms.	Klunder et al., 2012
Archeta domesticus (cricket)	a) Submerged in boiling water for 5 min. b) Stir-frying for 5 min.	Better TVC results were found by submerging in boiling water; No differences in Ent and BS.	Klunder et al., 2012
Brachytrupus sp. (large cricket)	Submerged in boiling water for 5 or 10 min.	No differences were found in TVC, Ent, or BS.	Klunder et al., 2012
Tenebrio molitor L. (mealworm larvae)	Submerged in boiling water in a 1/10 larvae/water ratio (w/v) for 10, 20, or 40 s, followed by chilling in an ice bath for 30 s.	TVC was reduced by between 5 to 6 log cfu/g, Enterobacteriaceae, BAL, and yeasts and molds almost disappeared. BS were maintained. Longer treatments were more effective.	Vandeweyer et al., 2017
Archeta domesticus L. (house crickets)	Submerged in boiling water (98 °C) for 5 min.	Not determined.	Kamau et al., 2018
Hermetica ilucens L. (Black soldier fly)	Submerged in boiling water (98 °C) for 5 min.	Not determined.	Kamau et al., 2018

Where TVC, total viable count; Ent, Enterobacteriaceae; BS, bacterial spores; and LAB, Lactic acid bacteria.

The high biodiversity and relative abundance of species play a key role in determining patterns of consumption, more so than agriculture and farming factors (Lesnik, 2017). It is estimated that more than 3,000 ethnic groups around the world consume insects in many forms, including hunter-gatherers (Ramos-Elourdy et al., 2012; Van Huis, 2016).

Cooking improves sensory quality through the formation of aromatic compounds as well as changes in color and texture. Some cooking procedures can increase the shelf-life of food products by reducing foodborne and degradative enzymes. From a nutritional perspective, cooking enhances the digestibility and bioactivity of proteins in the digestive tract; however, some nutrients could be lost through solubilization, leakage, inter- and intra-biochemical reactions, or new by- product (Caparros Megido et al., 2018). Heat treatment may induce proteolysis, lipid oxidation, and solubilization of vitamins and minerals (Juárez-Ortega et al., 2012). Protein denaturation, amino acid destruction or modification, and Maillard reactions may also occur. Lipids and fatty acids may be autooxidized, thermo-oxidized, or photo-oxidized (Frankel, 2012).

There are several traditional edible insect cooking techniques, including steaming, roasting, smoking, frying, stewing, and curing (see Figure 2; Ebenebe et al., 2015; Graboswski & Klein, 2017; Lautenshläger et al., 2016; Nonaka, 2009; Obopile & Seeletso, 2013; Ramos-Rostro et al., 2016; Shockley, Lesnik, Allen, & Muñoz, 2018). These techniques are preceded by blanching to reduce foodborne microorganism counts and to inactivate enzymes (Marshall, Dickson, & Nguyen, 2016). Obviously, each technology generates products with different sensory qualities and nutritional attributes (Kouřimská & Adámková, 2016; Tan et al., 2017).

In Latin America, Mexico is the country with the strongest tradition of eating insects. Grasshoppers and crickets ("*chapulines*") are commonly toasted or roasted in a pan without oil until the insects are crunchy. They are collected from the start of the rainy season in late spring until early winter. When the insects are boiled, the water used can be acidified with lemon juice or vinegar, and flavoring ingredients, such as garlic and onion, may be added. After toasting, when the insects are still hot, lemon, salt, and chili are usually added. During boiling, the insects turn a reddish color and aromatic compounds form. In Oaxaca, before blanching, the insects are fasted for 1 to 3 days food to avoid the generation of bitter tastes. Many traditional dishes are made with *chapulines*, such as tacos (corn tortilla with insects and hot sauce), hot chili sauces (chili sauce with *chapulines*), and "chiles rellenos" (chiles stuffed with *chapulines*). *Chapulines* are also consumed as a snack with alcoholic beverages (Cohen, Sánchez, Mata, & Montiel-Ishino, 2009; Ramos-Elourdy, 1997). Similar recipes use worms as an ingredient, such as the maguey worm (*Aegiale hesperiaris* and *Hypopta agavis*) and yellow mealworm (*Tenebrio molitor*). Eggs of the ant species *Liometopum apiculatum* ("*escamoles*") are usually cleaned and then fried with either butter or oil-fried spices and eaten in taco tortillas or in *tamales*. Other traditional culinary techniques have been described in cookbooks (Gordon, 2013; Ramos-Elourdy & Menzel, 1998). However, little information is available on the safety and global quality aspects of traditional cooking practices in Mexico. *Chicatana* ants (*Atta mexicana* and *Atta cephalotes*), queen ants collected at the beginning of the rainy season in southeast Mexico, are prepared in chili hot sauce (Reyes-Prado, Pino-Moreno, García-Pérez, & Carlos, 2016).

Invertebrates, which are very diverse and include many insect species (more than 758 morphospecies), are traditionally used as food by at least 32 Amerindian groups (Paoletti et al., 2000). Bees, wasps, caterpillars, and beetles are the insects that are the most commonly consumed (Paoletti et al., 2000); however, the culinary uses of these insects have not been fully explored. Thus, for the Awajun, an Amazonian indigenous people of Peru, beetles are the most culturally important edible insects, followed by ants, wasps, and flies. They are prepared in a variety of ways, mostly roasted (67%), toasted (10%), and fried (5%) until crispy. Some insects are eaten raw (Casas Reátegui, Pawera, Villegas Panduro, & Polesny, 2018).

In the Asia-Pacific region (North and Southeast Asia and Oceania), there is a long history of using insects as human food. In that region, consumption of insects is tied to dietary needs, cultural considerations, and insect availability. Insects are both harvested from the wild and farmed, and they are also used as animal feed for fish and poultry (Yen, 2015). In China, the consumption of edible insects is widespread, and although more than 324 species from 11 orders have been identified as edible, only 10 to 20 species are regularly used as food or medicine (Feng et al., 2017). The most popular insects are grasshoppers, silkworm pupae, wasps, bamboo insects, and stink bugs. Insects are usually fried (deep-fried or quick-fried), braised, stewed, boiled, steamed, or roasted. Although the use of insects is traditional, these are also considered a gourmet food in urban areas since they are perceived as "organic" (free of additives, pesticides, or other artificial compounds; Van Huis, 2016). Some insects are used in traditional medicine for their health benefits, some of which have been scientifically proven. For example, the Chinese caterpillar fungus enhances the immune system and has anticancer properties, and "ant alcohol" is used to improve human sex drive (Chen, Feng, & Chen, 2009; Feng et al., 2017). In Yunnan, a type of ant is used to make vinegar (Feng et al., 2017). In recent years, insect menus and cookbooks have been published in South Asia to teach consumers how to cook insects. Thailand is an example of a country with an important tradition of insect consumption that is becoming more westernized (Yen, 2015). Close to 200 species of insects are consumed in Thailand and are prepared in several innovative ways apart from the most common (roasting, frying, and steaming), such as curried, dipped (mixed with chili paste), and salted (Halloran, Vantomme, Hanboonsong, & Ekesi, 2015; Raheem et al., 2018). However, consumption is regional. For example, crickets are considered a specialty in northeastern Thailand, but remain rare in restaurants in Bangkok, where they are associated with rural poverty (Halloran et al., 2016).

Entomophagy is practiced on a large scale by the tribal communities of northeastern India. More than 82 insect species in nine different orders form a major component of their main nutrient intake and are reported as a normal part of the diet (Gahukar, 2018).

Termites, honey bees, grasshoppers, stink bugs, aquatic insects, and silkworms are cooked, roasted, pickled, or even consumed raw. Most of the traditional dishes are prepared by adding fresh or dried bamboo shoots. Crickets are mixed with salt before cooking, and certain species like *Oecophylla smaragdina* (Fabr.) and *Parapolybia varia* (Fabr.) are consumed raw (Mozhui, Kakati, & Changkija, 2017).

Africa has an impressive diversity of edible insects, with over 470 species identified as edible across the continent. The highest diversity is in the orders *Lepidoptera, Orthoptera,* and *Coleoptera* (Kelemu et al., 2015). Most edible insects are harvested from the wild (Mutungi et al., 2017). They are cleaned (with the removal, in some cases, of certain parts, such as wings and legs), and then roasted or boiled. Insects are also consumed fresh and raw. For animal feed, insects are sun-dried and ground to a powder and then added to different formulations. The edible caterpillar *Imbrasia epimethea,* consumed in Angola, is collected and washed in water. The guts are removed to avoid aftertastes and long hairs are removed to avoid toxicity. The caterpillars are boiled in salty water for 30 min until the water has evaporated. They are then sun-dried for 3 days, after which they can be stored at ambient conditions. They are fried before eating. When the thermal treatment was studied, no significant negative effects on nutritional value were found except for a slight decrease in monounsaturated fatty acids (Lautenschläger et al., 2017). In Tanzania, the grasshopper *Ruspolia differens* is eaten fresh or processed. In both cases, various pretreatments are performed, such as cleaning and boiling in salted water, with or without spices, for 15 min. After that, the grasshoppers can be eaten, but their shelf-life is very short (less than 48 hr) due to high water activity (Mmari, Kinyuru, Laswai, & Okoth, 2017). To increase their shelf-life, insects can be sun-dried for at least 2 days. Before being consumed, insects are smoked, toasted, or fried. Smoking in a wood stove for 2 to 4 days is common; toasting is done by placing the insects in a hot pan without oil until they turn brown and crunchy and acquire a meat-like aroma (Fombong et al., 2017). They are also fried in oil for 10 min until they turn to a brownish color (Mmari et al., 2017). In Botswana insects are commonly consumed either without any culinary preparation or the insects are sun-dried before being roasted, fried, boiled, or steamed and eaten as a snack. Larvae of dung beetles are grilled or fried in oil, and caterpillars are roasted in hot ash without salting, or salted, boiled, and sun-dried before consumption (Obopile & Seeletso, 2013).

In Western countries, there is no tradition of cooking insects, which significantly limits their culinary use. However, insects are used to ferment Milbenkäse cheese in Germany and France; mites are used to ferment some special varieties with a traditional lemon-like flavor (Brückner & Heethoff, 2016). Hence, edible insects are promoted as a snack and, like nuts, can be covered with chocolate, mixed into baked goods or sprinkled on salads. Mildly processed, fried, roasted, or finely ground, they are used to add a unique flavor to foods or to increase their nutritional profile. In recent years, insect cookbooks, TV shows, food fairs, and expositions have attempted to normalize entomophagy, in contrast to previous strategies that were based on promoting the novelty of the products (Shelomi, 2015). However, the current high price of edible insects, compared with other sources of animal and vegetal proteins, is an important economic barrier to expand their market (Ramos-Elourdy, 1997).

Finally, agricultural best management practices as well as good hygiene habits need to be established and employed by edible insect farmers in all countries to prevent food safety issues. Consequently, standard operating procedure manuals are needed and hazard analysis and critical control points will have to be developed for raw edible insects to ensure that their handling, processing, preservation, storage, and packing and/or distribution until consumption is carried out in the safest and most nutritious manner (Raheem et al., 2018).

Processing Technologies

The edible insect industry is moving ahead at staggering speed, and the demand for new products, both in recognizable form and as ingredients, is growing (Van Thielen et al., 2018). Under this scenario, it is necessary to review the main technologies used. The manufacturing processes start with the post-harvesting of raw insects and ends with the production of foodstuffs and wastes, some of which are recovered and reused as by-products (Raheem et al., 2018). Although the number of existing processes in the edible food industry is enormous and varies depending on the species used and the final product to be developed, most of them can be grouped into a relatively small number of operations with the same basic principles, focusing essentially on similar purposes (Earle, 1983). These are listed below.

Blanching

Blanching is a process wherein a food is placed in boiling water for a short period, removed, and then plunged into ice water or placed under cold running water to stop the thermal process (Xiao, Bai, Sun, & Gao, 2014). It is used as a pretreatment for most commercialized edible insects, at both the industrial and artisanal scales, to reduce microbial counts and to inactivate degradative enzymes responsible for food spoilage and poisoning. As shown in Table 2, blanching significantly reduces total counts of mesophilic bacteria and of yeast and molds; however, it is ineffective at eliminating, or even reducing, mesophilic bacterial spores. Blanching has also been reported to reduce counts of lactic acid bacteria and total psychrotrophic bacteria (Vandeweyer et al., 2017).

A slight increase in moisture has been reported after blanching, (Azzollini, Derossi, & Severini, 2016; Purschke et al., 2018a). In *T. molitor* L., an increase in moisture was reported (from 62.81% to 70.44% after 40 s), but water activity (available water) remained constant (0.96) (Vandeweyer et al., 2017). This effect could be due to the absorption and entrapment of water inside the larva of *T. molitor* L. just below the chitinous exoskeleton. However, no significant differences in chemical composition between fresh and blanched larvae were found (dry mass) (Azzollini et al., 2016). Changes in chemical composition are observable at longer times, mostly due to leaching of soluble nutrients that can affect the protein content (Niamnuy, Devahastin, & Soponronnarit, 2008). During the boiling process, some proteins undergo structural changes, including denaturation, crosslinking, and interaction with lipids and carbohydrates. As a result, the number of hydrophilic sites used for water binding may be reduced and sorption properties altered, making it necessary to conduct a more specific protein analysis (Azzollini et al., 2016).

Food color is of major importance for consumer acceptability but it has been poorly analyzed in edible insects. Color parameters have been studied in *T. molitor* L. flour, and luminosity (L) was found to decrease with the blanching treatment, probably due to a physical phenomenon whereby water in fresh tissues modified the refraction index when compared to dry samples. Therefore, a higher moisture value in blanched samples may have altered the luminosity, making the samples appear darker. The solubility of nutrients in blanched samples may increase certain secondary reactions, such as non-enzymatic browning reactions, which can reduce lightness (Azzollini et al., 2016).

Blanching treatments should be specifically designed for each insect species to improve antimicrobial effects with minimal quality loss. Blanching should minimize the microbiological risks associated with the consumption of edible insects, and it could be supplemented with techniques that can reduce the presence of bacterial spores (Caparros Megido et al., 2017). However, to meet the requirements of consumers and industrial processing, it is essential for these treatments to maintain the nutritional value of the products and other important quality attributes, such as texture and color.

Drying

Drying is the most widely used technology for increasing the shelf-life of foods. Drying techniques range from traditional methods (for example, roasting, frying, and sun-drying) to modern methods (for example, freeze-drying, microwave-assisted drying), as shown in Table 4. Drying can reduce the total water content and, therefore, its availability for degradative reactions, including enzymatic reactions and reactions initiated by spoilage microorganisms. Microbial growth depends directly on water activity (aw). The vast majority of microorganisms stop growing at aw <0.65. When aw is low, microorganisms show slowed growth, and when water conditions are appropriate, they can start growing again (Grabowski & Klein, 2016, 2017). A reduction of free water increases the dry matter concentration significantly without damaging the tissues or the physical appearance of foods and is an important step for food ingredient extraction (Lamidi, Jiang, Pathare, Wang, & Roskilly, 2019).

Table 3–Drying treatments used for edible insects.

Edible insect	Common name	Drying method	Conditions used	Reference
Ruspolia nitidula	Grasshopper	Air convention dryer.	80 °C/10 hr until moisture of 5% is reached.	Ssepuuya et al., 2017
Rhynchophorus phoenicis	Palm weevil	Solar drying Oven-drying Smoke-drying	5 days 50 °C/48 hr Exposure to smoke heat for 6 hr.	Tiencheu et al., 2013
Sternocera orissa	Giant jewel beetle	Oven-drying Freeze-drying Frying pan	66 °C/24 hr −55 °C/24 hr/085 mtorr 130-cm diameter, 50-mL tap water Fried without cooking oil	Shadung, Mphosi, & Mashela, 2012
Imbrasia epimethea	African moth	Oven-drying Solar drying	8 hr/80 °C 3 days	Lautenschläger et al., 2017
Macrotermes subhylanus	Winged termite	Solar drying	Approximately 30 °C RH 40% Time not indicated	Kinyuru et al., 2015
Polyrhachis vicina Roger	Black ant	Solar drying	(20–35 °C until dried, between 2 and 5 days)	Li et al., 2009
Ruspolia differens	Longhorn grasshopper	Freeze-drying	Phase (1) −50 °C/0.40 bars /48 hr Phase (2) −55 °C/0.021 bars /48 hr	Fombong et al., 2017
		Oven-drying	60 °C/24 hr	
T. molitor		Microwave-assisted drying	8, 10, 13, 16, 20 min 2 kw	Vandeweyer et al., 2017
T. molitor	Yellow mealworm	Oven-drying	Conventional hot air drying 60 °C/24 hr 80 °C/7 hr	Purschke et al., 2018a
		Freeze-drying	0.2 mbars/48 hr	
		Fluidized bed drying	Bed temperature: 60 °C Air outlet temperature: 55 °C Differential pressure bed: 15 bar Differential pressure filter: −1.3 bar Air flow: 500 m^3/hr	
		Oven-drying with air circulation	45 °C/48 hr	Viera-Alves, Sanjinez-Argandoña, Linzmeier, Cardoso, & Macedo, 2016
		Freeze-drying	Not indicated	Bußler et al., 2016
		Freeze-drying	Not indicated	Wynants et al., 2018
Cirina forda Westwood	Moth	Oven-drying	40 °C / 24 hr after boiling 2 hr	Omotoso, 2006
Rhynchophorus phoenicis F.	Palm weevil	Oven-drying	60 °C to constant weight	Idolo, 2010
Clanis bilineata	Dou-Dan	Ultrasound-assisted aqueous extraction (UAAE)	BILON-650CT multi-purpose constant-temperature ultrasonic extraction system equipped with one powerful ultrasonic transducer (20 kHz, 650 W)	Sun et al., 2018

Sun-drying, freeze-drying, and oven-drying are the preferred technologies for drying whole edible insects, while freeze-drying, oven-drying, and nonconventional drying techniques are used primarily for insect flours and powders. Drying and grinding whole, perfectly recognizable edible insects into unrecognizable powders is one of the preferred technologies for increasing human consumption of insects, mostly in the Western countries (Menozzi et al., 2017). Drying also increases product shelf-life during distribution and storage. However, regardless of the blanching and drying treatments applied to insects, they should be reheated before consumption to eliminate residual microorganisms. Boiling dried insects for 30 min has been found to be a good approach for eliminating total bacteria, *Enterobacteriaceae, Staphylococcus, Bacilli,* yeasts, and molds (Graboswki & Klein, 2016).

The most traditional drying technology is sun-drying, which is used mostly at the household level because of the low energy input (required to make products lighter for transportation; Azzollini et al., 2016). Sun-drying apparently prevents some microbial contamination and even reduces or removes some harmful compounds, such as neurotoxins; it also improves the total nutritional quality of the product by inactivating protease inhibitors (Niassy et al., 2016). However, the main limitation of sun-drying is the poor sanitary quality of both the process and the final product. The insect is considered dehydrated on the basis of appearance alone. Moisture content and/or water activity are not determined, given that it is a household process. Considering the limited hygiene practices applied during the process, the dried insects could become contaminated via contact with soil and air (Caparros Megido et al., 2018).

Smoking is a curing and thermal process. It is considered one of the most traditional techniques used for the preservation of all types of meat. The raw product is exposed to smoke produced by pyrolysis of wood. For insects, smoking is done in a dry environment and a curing process is performed simultaneously with drying. During the process, the combined action of enzymes and heat promotes protein and lipid changes (Tiencheu et al., 2013).

Table 4–New processing technologies used to extract different compounds of interest from edible insects.

Edible insect	Processing technology	Purpose	Conditions used	Reference
Tenebrio molitor L.	Cold atmospheric pressure plasma	Microbiological charge reduction	Surface dielectric-barrier air-discharge; sinusoidal voltage: 8.9 kV_{pp}; frequency: 3.0 kHz using air as working air with 12 mm of distance below the plasma source; continuous agitation. 350 rpm, 15 min. Thermal load <67 °C.	Bußler et al., 2016.
Pimelia spp.	Chemical extraction	Chitin extraction	Dried powder decolorization (6% NaClO, 40 °C, 10 min) and demineralization (1% HCl, 35 °C, 2 hr) and deproteinization (NaOH 1M, 70 °C, 10 hr). Wash until pH 7.0 and dried.	Kaya et al., 2016
Holotrichia parallela Motschulsky	Chemical extraction	Chitin extraction	Dried powder milled and treated with 1M HCl, 100 °C, 30 min to remove minerals and catechol; deproteinization: 1 M NaOH, 80 °C, 24 hr. Washed until pH 7.0. Decolorized ($KMnO_4$ (1%), 1 hr).	Liu et al., 2012
S. gregaria and *A. mellifera* (larvae and pupae)	Sonication assisted extraction	Protein extraction	Sonication (microtip probe Q SONICA); Amplitude: 70; pulse on time: 30 s; pulse-off time: 30 s: process time: 6 min; Centrifugation (3,000 × *g*, 20 min, 4 °C). Acidification at pI (4–5) and centrifugation (15,000 × *g*, 20 min, 4 °C); Neutralization (pH 7).	Mishyna et al., 2018
S. gregaria And A. mellifera (larvae and pupae)	Alkaline extraction followed by acid precipitation	Protein extraction	Dispersion on distilled water (1/15; v/v); pH = 10 (0.1N NaOH) and stirring 1 hr at 40 °C, Centrifugation (3,000 × *g*, 20 min 4 °C). Acidification at p*I* (4–5) and centrifugation (15,000 × *g*, 20 min, 4 °C). Neutralization (pH 7).	Mishyna et al., 2018
S. gregaria and A. mellifera (larvae and pupae)	Defatting	Protein extraction	Dispersion on hexane (1/5, w/v) and stirring 1 hr Re-extraction until clarity and air-drying (35 °C) overnight.	Mishyna et al., 2018
Tenebrio molitor L.	Supercritical CO_2 extraction	Oil extraction	400/250 bar, 45 °C, and 105 min.	Purschke et al., 2017
Tenebrio molitor L.	Dry-fractionation	Protein extraction	Blanching 10 min 1/12 (w/w) and shock-freezing (−38 °C, 20 min); thawing 1 hr, room temperature and drying treatments (see Table 3). Roller milling and sieve classification (pore size 355, 500, 710, 1000, 1400 μm).	Purschke et al., 2018a
Locusta migratoria L.	Enzymatic hydrolisis	Bioactive peptides production	Hydrolysis conditions (50 °C, pH 8.0, enzyme substrate ratio: 0.05, 0.5 and 1.0 mL/100 mL); Single treatments with alcalase, Flavourzyme, neutrase, and papain or combined treatment: one-step (simultaneously added) or two steps (after 1 hr each); dispersion in water 5% (w/v) (11,000 rpm, 60 s and stirring 1 hr, 50 °C); pH 8.0 addition of enzymes (24 hr, 50 °C). Reaction stopped (90 °C, 20 min).	Purschke et al., 2018b
Clanis bilineata	Ultrasound assisted extraction	Oil extraction	Freeze-drying and mixing with demineralized water (1/6; w/v), blending 5 min. Ultrasound (BILON-650CT multi-purpose); constant-temperature ultrasonic extraction system with 20X; Ultrasonic transducer: 20 kHz, 650 W; Treatment: 400 W, 40 °C, 50 min, and 2 s. Boiled 15 min and centrifugation (12,000 × *g*, 30 min, 4 °C).	Sun et al., 2018

(Continued)

Table 4–Continued.

Edible insect	Processing technology	Purpose	Conditions used	Reference
Tenebrio molitor, Alphitobius diaperinus, Acheta domesticus and Blaptica dubia,	Soxhlet extraction	Fat extraction	Soxhlet apparatus (6 hr, with petroleum ether as solvent); evaporation with rotary evaporator at 350 mbar, 40 °C, 30 min.	Tzompa-Sosa et al., 2014
Tenebrio molitor, Alphitobius diaperinus, Acheta domesticus and Blaptica dubia,	Water extraction	Fat extraction	Frozen insect mixed with water and blended 1 min, followed by 15 min of sonication; sieving (350 μm); centrifugation 15,000 × *g*, 30 min, 4 °C; after separation lipid fraction was centrifuged (15,000 × *g*, 15 min, 40 °C).	Tzompa-Sosa et al., 2014
Tenebrio molitor, Alphitobius diaperinus, Acheta domesticus and Blaptica dubia	Folch extraction	Fat extraction	Mixed ground powder with 200 mL dichloromethane/methanol (2:1) solution; shaking 20 s; sonication 10 min; shaking 2 hr; addition of 25 ml of water; centrifugation (1,006 × *g*, 20 °C, 20 min). Lipid fraction solubilized in organic solvents and filtered with dichloromethane. Evaporation of solvents 1.5 hr with rotary evaporator (800 mbar). Flushing with N_2 in water bath at 40 °C.	Tzompa-Sosa et al., 2014

Freeze-drying is the most widely used technique for laboratory analysis of the nutritional characteristics of insects. Given the low temperature used and the resulting water sublimation, microbiological and oxidative degradation ceases to a large extent, thereby yielding a high-quality final product with excellent nutritional value and a long shelf-life that is perfect for research but costly to scale-up to the industrial level. However, in products with high fat content, lipid oxidation could be promoted, as seen in *T. molitor* L., with an attendant decrease in protein solubility (Caparros Megido et al., 2017; Kröncke, Böschen, Woyzichovski, Demtröder, & Benning, 2018). Freeze-dried edible insects are commonly sold in Europe. Since most studies focus on physicochemical characterization and provide few or no details on the specific conditions applied, it is difficult to compare the results obtained, even for the same species (Caparros Megido et al., 2017).

Oven-dried products are comparable to freeze-dried ones, but they have lower energy input costs, reduced lipid oxidation, and high protein solubility (Fombong et al., 2017; Kröncke et al., 2018; Lautenschläger et al., 2017). When *T. molitor* larvae were dried after blanching in a forced-air oven to moisture equilibrium, the Page model showed the best fit with an $r^2 > 0.9932$ and the process presented a type II sorption isotherm (Azzollini et al., 2016).

Microwave-assisted drying reduced water activity after 16 min (aw < 0.30), leading to a significant decrease in the microbiological count. The suitability of microwave drying has been tested in *T. molitor L.* and final products with an aw below 0.6 were obtained. Fresh and blanched larvae were dried with minor changes in protein, fat, and ash contents observed in the larvae. Moreover, the browning index remained constant during 4 months of storage, and the only significant loss relative to freeze-drying consisted of vitamin B12 (Lenaerts, Van Der Borght, Callens, & Van Campenhout, 2018). However, more studies need to be carried out on how to maintain the sensory quality of the insects when microwave drying is used (Vandeweyer et al., 2017).

Kröncke et al. (2018) compared various drying processes with the aim of achieving a moisture content below 7.0% and water activity under 0.6 in *T. molitor* L. larvae: freeze-drying, fluidized-bed-drying, microwave-drying, vacuum-drying in a vacuum-oven, and conventional-hot-drying on a rotating rack. The authors concluded that all the drying techniques caused minor changes in protein, fat, and fiber contents.

During drying, the most visible quality change relates to color. When *T. molitor* L. larvae powder was oven-dried, color changes were observed, mostly when compared with fresh freeze-dried powders. Lightness values decreased with the blanching and drying treatments in comparison with fresh freeze-dried samples, as did yellowness (b*). Redness (a*) showed no significant changes. Oven-drying at 50 °C, followed by a blanching treatment, preserved the color in an economical way compared with lyophilization (Azzollini et al., 2016). The presence of brown products in which acylgylcerides were partially hydrolyzed, accompanied by an enrichment of the free amino acid pool, was observed in response to a high temperature and short treatment time (90 °C, 1.5 hr); however, these products had no significant impact on chemical composition (Melis et al., 2018). Furthermore, a dark color appearance was noted after microwave-assisted drying, and the products were considered over processed (Vandeweyer et al., 2017).

The lipid oxidation produced by the different drying processes negatively affects lipid quality and even the quantity (availability) of fats present in insects (Qiu, Chen, & Lin, 2019). In the case of *I. epimethea*, the monounsaturated fatty acid content was slightly reduced when oven-drying was used (Lautenschläger et al., 2017). During smoking, changes in both protein and lipids may occur. Smoke-drying was performed on *Rhynchophorus phoenicis* with the insects spread on a rack. They were exposed to smoke heat for 6 hr in a traditional way using wood and soot, as this was found to be the best method for maintaining the stability of the insects' lipid content (Tiencheu et al., 2013). In *T. molitor* L. freeze-drying oxidized the lipid fraction when compared with other drying techniques such as rack-oven-drying and microwave-drying with a 4-hydroxy-2-nonenal concentration of 111.03 μg/mL (Kröncke et al., 2018). Sun-drying caused an increase in the peroxide value of *Rhynchophorus phoenicis*, especially if the larvae were previously boiled, probably due to the low water content achieved at high temperature during this process (Tiencheu et al., 2013). Organic compounds can also be modified. Following sun-drying of *Polyrhachis vicina* Roger, an edible black ant, aldehydes appeared, free fatty acids increased, ketone levels decreased, and hydrocarbons were found in small concentrations (Li, Sihamala, Bhulaidok, & Shen, 2009). Dehydration affects the lipid fraction of edible insects by decreasing the level of triglyceride unsaturation (Tiencheu et al., 2013).

Protein solubility increased in *T. molitor* L. with vacuum-drying but it decreased with microwave-drying due to structural changes that microwaves generated in the protein fraction (Kröncke et al., 2018). Recently, Huang et al. (2018) compared the use of microwave-drying and oven-drying for processing black soldier fly (*Hermetica illucens* L.) larvae and found that although protein content and quality were similar (showing 40% essential amino acids), digestibility was significantly higher (greater than 75%) following oven drying compared with other drying technologies,

The application of different drying technologies affects some quality parameters beyond the obvious reduction in water. Protein functional properties, lipid oxidation, and color could be modified by the drying technology chosen and by the technological conditions applied. Therefore, the choice of drying technology should take in account the intended use of the insect and the form in which it will be consumed (whole, powdered ingredient, or sole ingredient). Sun-drying should not be considered a primary technology, given the associated high levels of lipid oxidation and poor hygienic conditions. The preferred industrial drying method is oven-drying since it produces the same final quality as freeze-drying in terms of protein, fat, and chitin extraction (Azzollini et al., 2016; Purschke et al., 2018a).

Processing technologies for extraction

New processing technologies for edible insects have been used mainly for protein, fat, and chitin extraction as shown in Table 5.

Protein extraction can be carried out using water, organic solvents, and enzymes to facilitate industrial processes. The extraction rate and characteristics are species dependent and could influence the extraction yield and the physicochemical, functional, and bioactive properties, depending on the solvent used (Bußler et al., 2016). In *T. molitor* and *H. illucens*, an aqueous extraction was used to prepare protein-rich intermediates for use in the production of feed ingredients. To isolate proteins from the insect flours, protein solubility was optimized by varying the pH, ionic strength, and extraction temperature of the solvent, and water extraction was then performed (Bußler et al., 2016). The protein extraction yield in *Acheta domesticus* was compared using hexane and water in different ratios. Results showed that hexane extraction was more effective for yield, color, crude protein, crude ash, and available carbohydrates. However, water extraction showed better emulsion and foaming capacity, as well as emulsion and foam stability (Ndiritu et al., 2017). Protein hydrolysates obtained from *Gryllodes sigillatus* crickets using alcalase improved emulsion and foaming properties. The increase in protein solubility also made the cricket protein extracts suitable for foods with a pH range of 3 to 7 and even alkaline conditions (up to pH 10.0) (Hall, Jones, O'Haire, & Liceaga, 2017).

Dry fractionation was used successfully with *T. molitor* L. to increase the yield of protein-enriched fractions, but results were dependent on the pretreatments and the drying treatment used before fractionation (Purschke et al., 2018a). The physicochemical characteristics of different fractions of *T. molitor* L. larvae depend on the drying pretreatment chosen and the sieving fraction analyzed. Results showed that pretreatment significantly affects the color, dimension, density, and other characteristics of the final dried powders. The sieving fractions had differing macronutrient compositions and the protein recovery yield was affected as well. The highest protein recovery was obtained with the particle size fraction 500 to 1000 μm. Fractionation is, therefore, a promising strategy for producing standardized insect-based intermediates with a view to industrial applications and consumer acceptance (Purschke et al., 2018a).

Mishyna, Martinez, Chen, and Benjamin (2018) compared the use of defatting, alkaline extraction, and sonication extraction to obtain a protein-rich powder from adult grasshoppers (*Schistocerca gregaria*) and from honey bee (*A. mellifera*) larvae and pupae. The three methods were found to be efficient for protein enrichment of the starting materials (powder) from both insects, giving a well-balanced composition of essential and nonessential amino acids. For both insects, the highest extraction rate was obtained with defatted raw powder (93.2% and 86.2%, respectively). However, the highest protein extraction rate was obtained with the sonication method (57.5 and 55.2 g/100 g dry weight, respectively). Both insect powders showed high foaming and emulsifying capacities that were comparable to whey protein. The highest values were obtained after 120 min for grasshopper powder extracted with sonication. However, changes in protein functionality were found to be related to alteration of protein charge, surface hydrophobicity, and distribution of proteins. In the case of the honey bee, high-molecular-weight proteins (75 to 200 kDa) were found, while in the grasshopper, the molecular weight of most proteins was $<$100 kDa. The extraction method modified the molecular characteristics of the proteins, such as surface charge and hydrophobicity.

Enzymatic hydrolysis has been studied mainly with a view to gaining a better understanding of the bioactivity of edible insects' hydrolysates after simulated gastrointestinal digestion (Nongonierma & FitzGerald, 2017), in particular angiotensin-converting enzyme inhibition (Dai, Ma, Luo, & Yin, 2013; Staljanssens et al., 2011), and antioxidant capacities (Zielińska et al., 2017). Changes in the techno-functional properties of enzymatic hydrolysates have been explored to a lesser extent, albeit with interesting results. In the case of locust *Locusta migratoria* L. (Purschke et al., 2018a), techno-functionality was improved by using various food-grade proteases (alcalase, neutrase, Flavourzyme, papain) alone or in combination with different enzyme-substrate ratios and hydrolysis times. The solubility, emulsifying, foamability, and oil absorption capacities were measured for all the treatments used (higher values were obtained for those with combined enzymes, sequential hydrolysis). This research showed the considerable potential offered by targeted enzymatic hydrolysis of edible insects.

Ultrasound-assisted aqueous extraction was used to extract oil from *Clanis bilineata,* an edible *Lepidoptera* species consumed in China, and compared with Soxhlet extraction (Sun et al., 2018). The highest oil yield (19.47%) was obtained with the ultrasound technique at 400 W ultrasonic power, 40 °C extraction temperature, and 2 s intervals for 50 min of extraction. In addition, ultrasound extraction improved the amount of polyunsaturated fatty acids extracted (56.89 g/100 g of oil) slightly, as well as the $\acute{\omega}$-3/$\acute{\omega}$-6 ratio (4.58). Antioxidant activity was also improved. Ultrasound extraction is considered a green technology that provides high returns on capital investment as a result of the reduction in processing time and the quantity of solvents used (Panja, 2018).

Cold atmospheric pressure plasma was applied to *T. molitor* L. flour as an innovative pretreatment and compared with thermal

Table 5–Edible insect commercial brands/companies and their marketed products.

Brand/Company	Products	Country	Source
Aldento	Pasta with *Tenebrio molitor*.	Belgium	https://www.goffardsisters.com
Aketta	Roasted cricket and powder.	USA	http://www.aketta.com/
Bitty Foods	All-purpose cricket flour.	USA	Sold on Amazon US
Chapul	Cricket energy bars and protein powders	USA	https://chapul.com
Chirps/Six Foods	Cricket chips	USA	Sold on Amazon US
Cricket Flours	Crickets and mealworm powder and whole cooked insects	USA	https://www.cricketflours.com
Exoprotein	Energy and protein bars with cricket protein and roasted, flavored crickets	USA	https://exoprotein.com/
Griopro	Cricket powder	USA	https://cricketpowder.com
Hotlix	Candies, lollipops and flavored crickets, scorpions, and larvae.	USA	https://hotlix.com
Entovida	Wide range of edible insect cooked ready-to-eat products: maguey worms, bamboo worms, scarab beetles, silkworms, ants, *chapulines* (grasshoppers), hornets, wasps and bees, crickets, mealworms, waterbugs, and scorpions.	USA	https://www.entovida.com
Meat Maniac	Seasoned and flavored crickets, termites, scorpions, mealworms, water bugs, rhino beetles, centipedes, cicadas, earthworms, shield bugs, zebra tarantulas, and locusts.	USA	https://www.meatmaniac.com
Newport Jerky Company	Cricket powder, canned scorpions, worm suckers, and mixed pupae.	USA	http://www.newportjerkycompany.com
All Things Bugs	Premium cricket powder (finely milled).	USA	http://allthingsbugs.com/
Bud's Cricket Power	Cricket protein powder	USA	https://budscricketpower.com
Bugeater Foods	Bugs-a-Roni (Pasta), Jump Taste (protein cricket powder).	USA	https://www.bugeaterfoods.com/
Critter Bitters	Cocktail bitters made with toasted crickets.	USA	http://www.critter-bitters.com/
Cricket Flours	Roasted cricket bites, cricket flours brownie mix, buffalo wing sauce cricket bites, cricket flours: pure powder, cricket salt (3 flavors).	USA	https://www.cricketflours.com/
LANDISH	Cricket powder superfood bars, Superfood protein powder (cricket powder), crickstart crackers.	USA	https://landish.co/
Detroit Ento	Cricket powder	USA	https://www.detroitento.com/
Don Bugito, Prehispanic Snackeria	Chile-lime crickets with pumpkin seeds, dark Chocolate covered crickets, spicy bugitos (worms), coconut toffee-brittle bugitos, cricket protein powder, granola bites powered by cricket flour, chinicuil (worm) salt.	USA	https://www.donbugito.com/
Entosense	Edible insect marketplace (from ants to zebra tarantulas).	USA	https://www.entosense.com/
Jurassic Snacks	Powdered peanut butter enhanced with cricket powder, cricket power powder.	USA	http://www.jurassicsnacks.com/
Lithic	Cricket protein powders, cricket protein bars, cricket pasta, pure cricket flour, all-purpose cricket flour, and cricket protein snack bars, among others.	USA	https://www.lithicfoods.com/#Products
Seek-Food	Cricket protein powders, gluten-free cricket flour, and paleo cricket flour.	USA	https://seek-food.com/
Crunchy critters	Chocolate covered, powder, and tubes of crickets, larvae, mealworms, buffalo worm, and locust.	United Kingdom	https://www.crunchycritters.com
Eat Grub	Energy bars, powders, roasted flavored crickets, buffalo worms, and mealworms.	United Kingdom	https://www.eatgrub.co.uk/
Kric8	Cricket protein powder and pasta.	United Kingdom	https://www.kric8.co.uk/
MiniFeasts	British dried-farmed mealworms (original, rosemary & salt, chili and lime, chili and red pepper) and insect flour.	United Kingdom	https://www.minifeasts.co.uk/
NutriBug	Cricket powder (75% protein), cricket powder (76% protein), cricket protein bars, and cricket protein pasta.	United Kingdom	https://nutribug.com/

(Continued)

Table 5–Continued.

Brand/Company	Products	Country	Source
Yumpa	Energy bars made with protein-packed cricket flour.	United Kingdom	http://www.yumpabar.co.uk/
Zoic Bar	High protein insect bars (cacao and tarragon).	United Kingdom	Facebook https://www.facebook.com/zoicbar/
Delibugs	Freeze dried, energy bars, candy & lollipops, spreads, made from a wide variety of insects.	Netherlands	https://delibugs.nl/
Burgs Foods	The Dutch bugburger.	Netherlands	http://www.burgsfoods.nl/
De Krekerij	Variety of products including crickets and grasshoppers, cricket meat, and catering service based on insect-based products.	Netherlands	https://krekerij.nl/
Kreca Ento-Food BV	Buffalo insect powder, freeze-dried crickets, whole insects (freeze-dried buffalo worms, grasshoppers, mealworms), insect powder (cricket, mealworm, grasshoppers).	Netherlands	https://www.krecafood.com/
Tiny Foods	Freeze-dried insects, seasoned insects (buffalo worms, house crickets, mealworms, grasshoppers), protein bars and energy bars, sweets and snacks, house crickets, mealworms, and so on.	Netherlands	https://tinyfoods.nl/
Tjirp Insect Food	Insect-based croquette snack.	Netherlands	https://www.tjirpfood.nl/
Europe-entomophagie	Dried insects, insect candy, and wholesale mealworms, scorpions, crickets, silkworm, caterpillars, ants, termites, and giant worms in kilo packs.	France	http://www.europe-entomophagie.com
Ïhou	The houtou products are sourced exclusively from their farming operation based in eastern France. Dehydrated crickets (salted, sweet, chili, and natural).	France	http://ihou.fr/
Insectéo	Black scorpions, mix of insects to discover, natural crickets, vodka brewed with different types of insects (scorpion, termites, chenille), curry, flavored roasted, flour, lollipops, paté, and cricket energy bars.	France	https://www.insectescomestibles.fr/
Insectéo	Flavored and seasoned crickets, mealworms, and scorpions.	France	http://www.insecteo.com
GRYÖ	Insect health food snacks (cricket powder bars).	France	http://gryo-food.com/#!home/mainPage
Jimini's	Spiced, Greek spice, fruity curry and paprika snack insects and high protein bars, insect flours for sport nutrition, high protein insect pasta, and so on.	France	https://www.jiminis.com/
Micronutris	Insect crackers (chili, thyme, sesame, tex-mex), cooking packs with dehydrated insects, high protein bars, including mealworm bars.	France	https://www.micronutris.com/fr/accueil
MinusFarm	Biscuits made from mealworms and crickets, Macarons made from mealworms and almonds, and so on.	France	https://minusfarm.fr/
Mon grillon (Inpulse protein) future foods	Cricket protein bar, High protein cricket powder.	France/UK	https://www.inpulseprotein.com/
Bug Biters Corporation	Chocolates with grasshoppers, cricket tortillas, cricket protein banana pancakes, cricket protein powder, and so on.	Mexico	On Facebook (www.facebook.com/Bug-Biters-162802594219573/)
Gran Mitla	Agave worm salt 100% chinicuil, grasshopper salt, ground agave worms.	Mexico	https://granmitla.us/
Griyum	Cricket protein powder (60% protein), and local cricket farms.	Mexico	https://www.griyum.com.mx/
Merci Mercado	Gourmet seasoned *chapulines* (grasshoppers), agave worm salt, red maguey worms, and ground grasshoppers.	Mexico	http://mercimercado.com

(Continued)

Table 5–Continued.

Brand/Company	Products	Country	Source
Snack insects	Roasted, chocolate covered, energy bars, candy & lollipops, and spreads of mealworms, and crickets.	Germany	https://wuestengarnele.de
BugFoundation	Germany's first insect burger made from buffalo worms.	Germany	https://bugfoundation.com/home-en.html
BenetoFoods	BenetoFoods is a new innovative food company that produces high-protein and high-quality foods based on barbequed protein. Three different flavors of cricket pasta.	Germany	https://www.benetofoods.com/
Brento	Delicious breads (Paleo-brento, Urkorn-brento, Ciabrento) with buffalo insect flour.	Germany	https://brento.de/
Instinct (Insek-tensnack)	Organic insect snacks (bars, apple and cinnamon, salty chocolate).	Germany	https://www.yourinstinct.de/
Isaac Nutrition	Insect flour (cooking and baking), protein powder with insects.	Germany	https://isaac-nutrition.de/
Imago-Insects	Cricket Burger Quinoa, Cricket Falafel Curry, Cricket Bolognese, Cricket Burger Classic, crispbread with flaxseed, and so on.	Germany	https://www.imago-insects.com/
Plumento Foods	Products such as pasta, biscuits, granola and croutons. These are high-quality, tasty products in which insects are disguised constituents.	Germany	https://plumento-foods.com/
Snack-Insects	Snack-Insects offers fine grasshoppers, crickets, and flour, buffalo worms from selected European breeders. Insect-based foods such as power bars, insect pasta and granola.	Germany	https://snackinsects.com/
Swarm Protein	Snack high protein bars.	Germany	https://swarmprotein.com/
Wicked Cricket	Insect power bars, insect snacks, crickets as snacks (salt, pepper and herbs).	Germany	https://wickedcricket.de/
Vitabug	Flavored roasted, chocolate covered, tortilla chips, and marshmallows of crickets, mealworms, and ants.	Australia	https://ediblebugshop.com.au/
Bugsy Bros	Crispy baked crickets, 100% cricket powder, protein ball mix, sample packs, among others.	Australia	http://bugsybros.com.au/
The Cricket Effect	Protein packed muesli bars with cricket flour.	Australia	https://thecricketeffect.weebly.com/
The Cricket Bakery	Insect-based baking blends (banana bread, protein pancakes, protein powder, and seedy paleo loaf).	Australia	https://thecricketbakery.com/
Grilo Protein	Organic cricket protein powder, organic super greens & cricket, organic roasted crickets, organic cricket energy bar (different flavors).	Australia	https://griloprotein.com.au/
GrubsUp	Whole roasted crickets, whole roasted mealworms, cricket energy bar, cricket hazelnut dukkha, and cricket powder.	Australia	https://grubsup.com.au/
Leap Protein	Peanut Butter Cricket Protein Bar, Cricket Skin Glow Bar (Orange & Goji Berri), Cricket Protein Bar (Chocolate Coconut).	Australia	https://www.leapcricketproteinbars.com/
Primal Collective	Roasted crickets.	Australia	https://www.optimoz.com.au/products/roasted-crickets-edible-bug-protein
Hopper Foods	Flavored granola bars with cricket flour	Australia	https://hopperfoods.com.au/
Die Wurmfarm	Worm Gourmet Gastronomy (mealworm based products).	Austria	https://www.diewurmfarm.at/gastronomie/
Insekten Essen, Zirp Insects	Mealworms, buffalo worms, locusts, crickets, Sauces (pesto and basil, tomato pesto with buffalo worms), bug snack, Zirp Zotter (dark chocolate 70% and dark chocolate 80% and Zirp Buffalo Worms)	Austria	https://www.zirpinsects.com/
Beesect: Beetles Beer	A unique beer, flavored with protein from insects.	Belgium	http://www.beetlesbeer.be/en/
Bugs World Solution Food	The LIZZY bitterballen; A healthy variant of the typical "meat bitterball," insect snacks, etc.	Belgium	http://www.bugsworldsolutionfood.com/#3

(Continued)

Table 5–Continued.

Brand/Company	Products	Country	Source
Goffard Sisters	Artisanal pasta (enriched with mealworms).	Belgium	http://www.goffardsisters.com/
Kriket	KRIKET is a delicious snack made from a mixture of nuts, grains, seeds and crickets, and 100% sourced in Brussels.	Belgium	https://kriket.be/
Little food	Powder, tapenade, crickers (Cricket Crackers) and dried crickets.	Belgium	https://www.littlefood.org/
Nimavert	Ravioli and croquettes with mealworms as a main ingredient.	Belgium	https://www.nimavert.be/nl
Bite Snacks	Energy bars and cricket protein powders.	Canada	https://bitesnacks.com/
C-FU Foods	Extracts the protein from crickets and makes their own cricket-tofu: C-FU.	Canada	https://cfufoods.com/
CrikNutrition	Protein powders (crickets, chocolate, sweet vanilla, etc.).	Canada	https://criknutrition.com/
Coast Protein	Protein energy bars, cricket protein powders.	Canada	https://www.coastprotein.com/
Fit Cricket Nutrition	Cricket protein powder and protein bars.	Canada	https://fitcricket.com/
Inspiro Foods	Insect protein products	Canada	http://www.insprofoods.com/
NÄAK	Cricket products: energy bars, energy bits, high protein bars, cricket protein powder.	Canada	https://naakbar.com/
Tottem Nutrition	Pasta + cricket powder	Canada	https://tottemnutrition.co/
uKa protéine	Cricket flour, roasted crickets.	Canada	https://ukaproteine.com/
Yes Crickets	Crickets (*Acheta domesticus*). Premium Canadian cricket farm growing crickets and also selling flavored dry-roasted crickets and protein powder.	Canada	https://www.yescrickets.com/
Entomofarms	Cricket powder, mealworm protein powder, seasoned and flavored crickets and mealworms.	Canada	https://ca.entomofarms.com
Bugsolutely China	Making the Bella pupa silkworm snack.	China	https://www.bugsolutely.cn/eng/
BioHexaPro	Will produce burgers, protein bars, and cricket flour for Agriculture and Pet Food. (Started January 2018)	Colombia	https://www.biohexapro.com
1900 Especies	Farming, commercialization and traditional cooking methods of insects for human consumption.	Colombia	https://1900especies.co/
Sensbar	Protein bars & energy bars made with cricket flour (different flavors).	Czech Republic	https://www.sensbar.com/en/
Crickster	Cricket protein flour and whole, Buffalo worm flour and whole, Snack crickets (different flavors umami, Mexican and Italian).	Denmark	https://crickster.dk/
Enorm	Danish company making insect bars with lesser mealworm (and other snacks with chili, onion, and so on).	Denmark	http://www.enormfood.com/
Syngja	Cricket shot with different flavored drinks (apple ginger, beetroot seaberry, and spirulina acerola).	Denmark	https://syngja.dk/
Wholi foods	Used to be known under the brand "Dare to eat." Makes cricket snacks and a protein bar called "Buff bar," buffalo larva flour, Dare squares (chili, chocolate & cricket), peanut butter and buffalo worms, and so on.	Denmark	https://wholifoods.com/
Entis	BUGBITES® is an insect and vegetable protein-based snack, Sirkkis® is a tasty protein product containing vegetable proteins and cricket powder, Sirkkasuklaa®-chocolate covered crickets.	Finland	https://www.entis.fi/
Finsect/GRiiDY	Northern forest cricket crackers, Sea salt roasted crickets, Soy and ginger roasted crickets, Garlic salted roasted crickets, and warm chili roasted crickets.	Finland	http://www.finsect.fi/
Griinsect	Griinsect cricket crackers (seed-cricket-snack).	Finland	http://www.griinsect.fi/
Leader Zircca bar	Nutritious and sustainable bars made of cricket's protein.	Finland	http://www.leader.fi/eng/products/zircca/

(Continued)

Table 5–Continued.

Brand/Company	Products	Country	Source
Nordic Insect Economy	Dried insects.	Finland	http://nie.fi/
Savonia Grasshopper	Grasshopper (hot pepper, herb-garlic, sweet), Roasted hopper, Grasshopper chips.	Finland	https://sirkkoja.fi/
Biteback	Using edible insects (meal worm oil) as a healthier and more sustainable source of fats and oils.	Indonesia	http://www.bitebackinsect.com/
Crické	Cricket crackers and cricket powder.	Italy	https://crickefood.com/
Italbugs	Italian food (pasta) and sport supplements (protein powder and bar) from insects.	Italy	http://www.italbugs.com/
Insetti commestibili	A wide variety of products: Mix of insects (dehydrated), cricket flour, insect protein bars, silk worm flour, canned insects, and so on.	Italy	http://www.insetticommestibili.it/
The flying spark	Working with fruit fly larvae. The currently produce whole high-quality protein powder, reduced-fat powder, dry larva, and larvae oil.	Israel	https://www.theflyingspark.com/
Bugmo	Cricket bars and cricket flour.	Japan	https://bugmo.jp/
Eat Crawlers	Salted caramel scorpions, Lightly salted insect mixture, Zebra tarantula (dehydrated), freeze-dried crickets and scorpions.	New Zealand	https://www.eatcrawlers.co.nz/
Live Longer	Cricket flour (100% organic), cricket protein bars.	New Zealand	https://livelonger.co.nz/
Primal future	Premium Organic Cricket Powder.	New Zealand	http://www.primalfuture.co.nz/
Acheta	Cricket powder.	Norway	https://acheta.no/
Invertapro	High-quality protein and plant nutrition based on the *Tenebrio molitor* larvae (Mealworm) and *Hermetia illucens* larvae (Black soldier fly).	Norway	https://www.invertapro.com/
UNIKMAT	Insect flour, insect protein bars, whole *billbill* larvae, Siris flour (100% *Acheta siris*).	Norway	https://www.unikmat.no/
Urbanmat	Breeding and selling insects both whole and prepared.	Norway	https://www.urbanmat.no/
Mopani Queens	The only company in South Africa and sells flavored Mopani Caterpillars or Mopani Worms. Barbeque, chili, chutney, and the original salted flavor.	South Africa	Mopani Queens Facebook page.
Edible-bug	Dried edible insects, edible cranberry cookie, and meal worm powder.	South Korea	https://edible-bug.co/
EntomaFoods	Snacks, whole dried insects, insects' flours, protein bars, seasoned dried *Tenebrio molitor*, seasoned grasshoppers, and so on.	Spain	https://entomafoods.com/es/
EAT:EM	Cricket bars, Crisp Bread (with crickets), and crackers.	Sweden	http://www.eatem.se/
/NUTRIENT	The first Swedish entrepreneur breeding its own mealworms.	Sweden	https://www.nutrient.se/
Tebrito	Working on their own protein product based on mealworms.	Sweden	http://www.tebrito.se/
Essento	Mealworms burgers and balls.	Switzerland	https://essento.ch/
Entomos	Swiss organic mealworms *Tenebrio*, house crickets' *acheta*, edible grasshoppers (lyophilized), grasshoppers *Locusta*, protein balls with cricket, pastry with cricket flour, crisps with organic *Tenebrio molitor*, among others.	Switzerland	https://entomos.ch/
Insekterei	Paté with mealworm, crispbread with cricket flour, high-quality protein cricket balls, and dried crickets' powder (Protein 60%).	Switzerland	https://insekterei.ch/
Hiso	Wide range of cooked and flavored silkworms and crickets.	Thailand	http://www.hisoapero.com
JR Unique Foods, (sold also under the brand name of *EcoEat*)	Cricket powder, fried cooked pupae, and scorpions.	Thailand	https://jrunique.com

(Continued)

Table 5–Continued.

Brand/Company	Products	Country	Source
Next-food	Flavored crickets, Plain roasted scorpion, tarantulas, mealworms, giant water bug, giant worms, silkworms, locust, grasshoppers, diving beetle, weaver ants, bamboo worms, cicada, and ants.	Thailand	https://www.next-food.net
Bugsolutely	Cricket pasta, snack with insect powder (silkworms), *Bella Pupa*.	Thailand	https://www.bugsolutely.com/
Get propro	Cricket protein bars with different flavors,	Thailand	https://www.getpropro.com/
Thailand Unique	Canned, bulk, candies and powders of a wide variety of insects including crickets, dung beetles, larvae, pupae, shield bugs, scorpions, black ants, cicada, weaver ants, silk month pupae, ant eggs, squash bugs, and grasshoppers.	Thailand	https://www.thailandunique.com

(*All web pages accessed April 01, 2019*).

treatments between 20 and 140 °C at different times to reduce microbiological loads. Although high temperature treatments (120 to 140 °C) inactivated all the microbiota present in the insect, the use of cold atmospheric pressure plasma reduced microbiological loads by up to 3 log units, and the overall quality of the final product was better. The *T. molitor* L. flour through cold atmospheric pressure plasma processing showed better thermo-functional properties such as water and oil binding capacities and protein solubility when extraction was performed at pH 4.0. Some changes in protein composition were also found as a decrease in low-molecular fractions (15 to 20 kDa) and an increase in high-molecular fractions (>60 kDa; Bußler et al., 2016).

Purschke et al. (2017) studied supercritical CO_2 extraction of edible insect oil from *T. molitor* L. larvae. The authors found that *T. molitor* oil composition and acidity was influenced by the extraction parameters. Extracted oils contained 72% unsaturated fatty acids, and an oleic acid content close to 42% with a high oil extraction yield (95%). Oil composition and acidity were affected by the extraction parameters, with better results obtained at low pressures and temperatures. However, the oil composition was similar to that of hexane-extracted oil.

Tzompa-Sosa, Yi, van Valenberg, van Boekel, and Lakemond (2014) extracted lipids from *Tenebrio molitor*, *Alphitobius diaperinus*, *Acheta domesticus*, and *Blaptica dubia* using three methods: Soxhlet extraction, aqueous extraction, and Folch extraction. *T. molitor* had the highest lipid content among the four species, and the highest extraction yield was obtained with the Folch extraction method. The method used affected the quantity of lipids obtained as well as the lipid profile. Water extraction gave the best lipid profile quality, even when the extraction yield was the lowest.

Chitin and chitosan are extracted from the exoskeletons of a variety of edible insects. This is the case for the beetle *Holotrichia parallela* Motschulsky that is captured for the control of pests in fields. This insect's chitin was compared with the commercial α-chitin extracted from shrimp. The beetles' chitin showed similar characteristics to the chitin obtained from shrimp. Chitin from *H. parallela* could be an alternative source of chitin (Liu et al., 2012). A similar extraction was performed on exoskeletons of *Pimelia* spp. The extracted chitin and chitosan were found to be nontoxic and showed antimicrobial activity against *C. albicans* and *L. monocytogenes*, and therefore has potential for use in food preservation. The oil-binding properties of chitin are well documented and can be used to design potential oil-binding food supplements (Kaya, Sargin, & Erdonmez, 2016).

Three-dimensional food printing technologies have recently been used to extrude insect paste filaments as a new method for creating foodstuffs. This is an innovative manufacturing process whereby a digitally controlled robotic construction process can make three-dimensional objects based on layer-by-layer deposition (Severini, Azzollini, Albenzio, & Derossi, 2018; Soares & Forkes, 2014). Previously ground microwave-dried *T. molitor* larvae were used to enrich a wheat dough, and the three-dimensional printing process was performed using a three-dimensional printer model equipped with a clay extruder. The dough was pushed by a piston at a pressure of 4 bars through a plastic tube on the head of the extruder. The printing conditions were as follows: print speed 30 mm/s, travel speed 50 mm/s, layer height 0.5 mm, and nozzle size 0.84 mm. The printed snacks reproduced the overall structure of the designed object, but the addition of different concentrations of the insect powder modified the printability of the dough and the morphological and microstructural properties of the final product. However, the nutritional quality was greater than that of the nonsupplemented wheat dough (Severini et al., 2018).

Borremans et al. (2018) carried out marination and fermentation of *T. molitor* larvae, a novel culinary practice, and found that these processes provided final products with a long shelf-life; they did not evaluate consumer acceptance. In the study, blanched larvae were marinated for 6 days in either red wine or soy sauce. Both treatments were effective in preventing the proliferation of spoilage microorganisms (total viable aerobic microorganisms, *Enterobacteriaceae*, and bacterial endospores), and mealworm shelf-life was extended for 7 days relative to larvae that were only blanched. In the fermentation treatment, larvae were crushed prior to fermentation in order to obtain a paste and were inoculated with a mixture of *Pediococcus acidilactici, Lactobacillus curvatus,* and *Staphylococcus xylosus* meat starter, supplemented with 2.8% NaCl (w/w), 0.75% D-(+)-glucose (w/w), and 0.051% $NaNO_2$ (w/w), and then incubated at 35 °C for 2 weeks until fermentation was complete ($pH < 5.0$). The shelf-life of the two products was not determined (Borremans et al., 2018).

Storage

In many parts of the world, "ready-to-eat" insects are sold in local markets after sun-drying, roasting, or frying in bulk without appropriate hygienic handling. When insects have not previously been subjected to a thermal treatment, such as boiling, they may contain a high microbiological load and they can be recontaminated and/or cross-contaminated. Therefore, it is necessary to process, pack, and store them properly to minimize the bacterial loads. Since blanching does not eliminate bacterial spores (Belluco et al., 2013; Caparros Megido et al., 2018), to completely sterilize insect flours, thermal treatment at a temperature between 120 and 140 °C needs to be applied for 15 min (Bußler et al., 2016). Recontamination and cross-contamination can occur when products are improperly packed and stored, even if a blanching process was performed. In the case of blanched, dried, and ground *A. domesticus,* the flour could be preserved for 16 days with refrigeration (5 to 7 °C), but only 4 days at room temperature (28 to 30 °C; Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012).

In general, storage conditions depend on the insect species and on whether the product is sold as whole and ready-to-eat insect or as a powder, after a drying process. Each product type displays a specific pattern of shelf-life, consisting of the sum of the raw product initial counts, plus modifications due to processing as well as secondary contamination (Grabowski & Klein, 2017).

Recently, Adámek et al. (2018) analyzed the microbiological quality of the following long-term-stored edible insects: yellow mealworm (*Tenebrio molitor*), lesser mealworm (*Alphitobius diaperinus*), field cricket (*Gryllus assimilis*), and migratory locust (*Locusta migratoria*). All the samples were found to be safe for human consumption. The most suitable processing for long-term storage was killing with boiling water, drying at 103 °C for 12 hr and subsequent hermetic packaging.

In the case of fresh insects, freezing (−20 °C) is recommended as a storage method to maintain their microbial quality instead of refrigeration (5 to 7 °C; Belluco et al., 2013). For dried and powdered edible insects, refrigeration is the best method for avoiding oxidative and microbiological degradation. Similar results were obtained for field crickets (*Gryllus bimaculatus*) and superworms (*Zophobas atratus*) (Grabowski & Klein, 2016).

When refrigeration is combined with vacuum or modified atmospheres, the shelf-life of the products increases markedly. Storage under vacuum and darkness can improve the shelf-life of whole edible insects even when stored at room temperature (Ssepuuya, Aringo, Mukisa, & Nakimbugwe, 2016). Vacuum packing improves the microbiological quality of the product, while darkness prevents lipid oxidation. For instance, whole *Ruspolia nitidula* (a grasshopper), when pan-fried and dried, maintained edible quality (sensory and microbiological) for 12 weeks. No significant difference in total plate counts was observed when vacuum (reduced pressure) was applied (Ssepuuya et al., 2016). In addition, vacuum storage can maintain the microbial (total plate count), sensory (overall acceptability), and chemical properties (acid value, peroxide value, and thiobarbituric acid values) of ready-to-eat *R. nitidula* for 22 weeks similarly to low-temperature storage (Ssepuuya, Mukisa, & Nakimbugwe, 2017).

A modified atmosphere consisting of 60% CO_2 and 40% N_2 was used to store minced meat-like products from *T. molitor* and *Alphitobuous diaperinus* larvae under refrigeration. A significant reduction in microbial growth was observed relative to samples stored in normal atmospheric conditions. The *T. molitor* aerobic count remained low (1.0 log CFU/g) after 28 days when stored under modified atmosphere; however, the total aerobic count was 6.9 log CFU/g for samples stored under ambient conditions. By contrast, *A. diaperinus* could be stored for only 14 days under modified atmosphere conditions (1.9 log CFU/g). Bacterial community composition differed between the two stored products but was significantly lower than that found in raw minced meat from traditional sources. The product shelf-life also depended on the original minced species used. However, the specific presence of food pathogens should be analyzed before this type of product is stored in modified atmospheres (Stoops et al., 2017). Similar results were obtained by Flekna, Mäke, Bauer, and Bauer (2017), who found that under anaerobic conditions, *T. molitor* (30% CO_2; 70% N_2) can be preserved for 3 weeks under refrigeration without microbial changes or oxidative deterioration.

Commercialization of Edible Insects

Edible insects have traditionally been sold dried and/or ground and are sometimes marketed as flours, heat-dried larvae, pupae, or whole adult insects. Edible insects are available in the market in a variety of forms: canned, bulk, powder or flour products, snacks, candies, chocolate-covered, and liquor infusion. Thailand Unique™ (JR Unique Food Ltd.), an online retailer, sells a range of products, from canned items to more processed forms, such as pasta and protein shakes. Over the last 10 years, several companies and startups around the world, mainly in Europe, South Asia, and North America, have been created to commercialize insect-based food products for human consumption. Approximately, 133 of these brands/companies are listed in Table 5. On Amazon.com (USA) alone, more than 100 insect-based food products are sold as gourmet foods (https://www.amazon.com/s?k=edible±insects&__mk_es_US=%C3%85M%C3%85%C5%BD%C3%95%C3%91&ref=nb_sb_noss_2), most of which are sold in whole form. On eBay, over 250 edible insect' food products are available (https://www.ebay.com/sch/i.html?_from=R40&_trksid=m570.l1313&_nkw=edible±insects&_sacat=0). For instance, the French brand Insectes Comestibles™ (www.insectescomestibles.fr) sells curry, lollipops, paté and energy bars, and other products made from crickets (*A. domesticus*). According to our research on insect-based food businesses, the main commercial forms are flavored snacks, energy bars, and powders (sold mainly as sports supplements) and the most widely sold insects are crickets, grasshoppers, and mealworms (see Table 5).

Due to their high levels of proteins and well-balanced amino acid profile, insects have attracted the attention of researchers as potential food ingredients for sports nutrition supplements, such as protein concentrates/isolates, flours, energy bars, protein shakes, and hydrolysates. These products, most of which are made with crickets and mealworms, are sold in specialized stores, (see Table 5). *T. molitor* L. has been used to fortify a wide variety of foods, such as corn tortillas, cookies, and meat-like products. In corn tortillas, this insect has been used as a supplement (2%, w/w). When corn tortillas supplemented with 7.14% *T. molitor* larvae flour, the supplemented tortillas were 2% higher in protein (Aguilar-Miranda, López, Escamilla-Santana, & Barba de la Rosa, 2002). Freeze-dried *T. molitor* L. larvae were used to enrich emulsified sausages, resulting in an improvement in emulsification properties (Kim, Weaver, & Choi, 2017). Cho, Zhao, Kim, Kim, and Chung (2018) developed a liquid seasoning fermented by *Aspergillus oryzae* and *Bacillus licheniformis* for addition to the soy sauce fermentation process, producing sensory properties similar to those of the original soy sauce; however, 1.5 to two times more essential amino acids than the soy-fermented sausage.

Minced meat-like products with a mealworm larvae content of more than 90% were successfully produced and stored in modified atmosphere packaging for 14 to 28 days, depending on the insect species used (Stoops et al., 2017). Meat batters containing 5%, 10%, and 15% edible silkworm pupae and transglutaminase were added to frankfurters, resulting in higher protein and ash contents and significantly lower cooking loss weight than in the control. In addition, the silkworm pupae meat batter showed an increase in pH value, viscosity, and texture properties compared to the control (Park et al., 2017).

Sun-dried termites were used to formulate an extruded product (winFood®) containing germinated amaranth, white corn, soybean oil, and sugar to combat infant malnutrition in Kenya (Kinyuru et al., 2015). Prior to extrusion, the insects were subjected to blanching (95 °C, 1 min) and oven drying (120 °C, 1 hr). Extrusion was carried out using a locally fabricated extruder with a barrel length/diameter ratio of 25. The extrusion conditions were as follows: feed moisture content 12% to 14.4%, moisture injection 9%, feed rate 33 kg/hr, screw-speed 300 rpm, and barrel temperatures 70 °C (zone 1), 100 °C (zone 2), and 127 °C (zone 3). Results showed a low-cost process and a final product with good nutritional value and a shelf-life of 6 months (Kinyuru et al., 2015). The macro-termite *Macrotermes subhyalinus* was used to design sorghum biscuits. The termites were cleaned and oven-dried at 65 °C for 72 hr before blending. The flour was dispersed in hexane for 1 hr, and the mixture was decanted under reduced pressure to separate the solvent. The residue was dried at room temperature for 24 hr and preserved at 4 °C. Biscuits were formulated with different concentrations of the protein extracted from the insect. Results showed a significant improvement in the protein and mineral contents of the biscuits. The sensory analysis showed that the biscuits are acceptable with an insect flour content of up to 25% (Niaba Koffi et al., 2013).

Flour produced from the cockroach *Nauphoeta cinerea* was used to enrich bread at concentrations between 5% and 15%. The flour presented satisfactory sanitary conditions with a good nutritional profile due to the amino acid and fatty acid contents, and addition of the insect flour did not alter the technical or sensory characteristics (de Oliveira, da Silva Lucas, Cadaval, & Mellado, 2017).

Crickets have been used to formulate cookies with amaranth, rice, oatmeal, chocolate chips, butter, walnuts, and so on. (Ayieko, Ogola, & Ayieko, 2016; Ryu, Shin, Kim, & Kim, 2017) and these products are well accepted by children (Ayieko et al., 2016).

The most recent research has focused on the use of edible insects as food ingredients to fortify more traditional forms of food such as bread, cookies, pastas, burgers, and sausages, thereby increasing their nutritional value. This trend has allowed the commercialization of insect-based food products and ingredients that go beyond traditional flavored snacks, and has given rise to alternative ways to include them in our daily diet, in addition to harnessing all the environmental, technological, and nutritional advantages associated with insect agriculture.

Conclusions

New food processing technologies are required to formulate functional ingredients and snacks in whole and recognizable forms, in order to promote entomophagy. The benefits of increasing insect consumption have been widely explored, but not the technological and processing approaches that can help achieve this goal. Early adopters, mostly the younger generation, are the main population segment that should be targeted to change negative attitudes toward insect consumption. Young people are demanding products that look different from those currently incorporated into daily meals and snacks (for example, burgers and cookies) and are somewhat interested in healthy and ethnic foods. The consumption of whole insects is the main issue that needs to be addressed in the short term, possibly through offerings such as snacks and energy bars. Some insect-based ingredients have substantial potential owing to their nutritional characteristics and functional properties in food, pharmaceutical, and cosmetic products. For instance, protein concentrates and/or isolates derived from insects have high foaming and emulsifying properties, as well as other techno-functional capacities. Insects are rich in polyunsaturated fatty acids and have a high $\acute{\omega}$-3/$\acute{\omega}$-6 ratio. The chitin composition of insects is similar to that of shrimp, making them a feasible and sustainable option for replacing some currently available functional ingredients. These aspects should be a focus of future research and technological development.

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Author Contributions

Melgar-Lalanne and Hernández-Álvarez collected most of the data, wrote the draft manuscript, and suggested the original idea for this review. Salinas-Castro collected and reviewed the data for the insect farming section. All of the authors reviewed the entire document and approved the final version.

Conflict of Interest

The authors do not have any conflicts of interest to declare.

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