Chapter

Perspective Chapter: Technological Strategies to Increase Insect Consumption – Transformation of Commodities Meal and Oil into Food/Functional Ingredients

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Abstract

Insects have been proposed as an alternative source of nutrients to conventional foods, mainly protein sources because they have excellent nutritional quality and are sustainable. However, there are multiple barriers to mass consumption of insects, primarily the rejection and neophobia they provoke in individuals from Western cultures. Several studies have indicated that the acceptance of insects as food ingredients could be improved "if insects did not look like insects." Therefore, the focus of current research is to transform commodity-type ingredients such as insect flour and oil through various technologies applied in the food industry such as protein concentration, encapsulation, hydrolysis, fermentation, deodorization, to develop food ingredients with better sensory and technological properties are better accepted by people as a part of their diet. Interestingly, some food ingredients obtained from insects also have functional properties that could increase interest in consumption. These aspects will be reviewed in this chapter for further consideration of insects as food ingredients of the future.

Keywords: insect, functional ingredients, sensorial properties, food, feed

1. Introduction

The size of the world population and its accelerated growth are the greatest threat to humanity in terms of sustainability. The world population is expected to increase to 9.8 billion people by 2050 [1], requiring a 70–100% increase in food production to feed the world. Population growth could soon outstrip food production [2, 3]. Among the foods produced to feed humans and animals, those of animal origin are recognized as the least sustainable. For example, the production of 1 kg of beef protein has a carbon footprint between 45 and 640 kg CO_2 equivalents and a land use of 37–2100 m^2 [4, 5]. Enteric-derived methane from ruminant livestock accounts for 17–37% of the methane emitted to the atmosphere from human activities [6–8]. Ingredients of animal origin are the most complex to replace in animal and human diets in terms of nutritional needs because: i) They have high crude protein content (20–23% for meat and fish and 40–70% for animal meals); ii) have highly digestible amino acids (close to 85–90% for meals and even higher for meat) [9–13]; iii) have a high content of essential amino acids [14, 15], iv) have highly bioavailable organic minerals, such as heme iron and zinc [14, 16], and v) have a high concentration of vitamins. Vitamin B12 is only found in foods of animal origin [17]. Several of these characteristics are not present in plant sources [18–21]. In addition, projections indicate that the price of animal-derived meat and meals will increase steadily [22].

For these reasons, there is an urgent search for new sustainable and moderate-cost protein ingredients with nutritional properties similar to those from an animal origin. Among the available alternatives are protein ingredients obtained from non-conventional raw vegetable materials such as chickpeas, lentils, beans, peas, broad beans, and others [23–25]. However, they do not always meet the demanding amino acid requirements (in terms of digestibility and essential amino acid supply) of animals and humans [26, 27]. Other alternatives are the development of protein ingredients from microalgae, algae, yeasts, fungi, microorganisms, and the re-processing of animal or marine waste [28–33]. The drawback of these alternatives is their low productive volume, which is extremely variable, and their high cost. Technological strategies have also been applied to protein ingredients, such as fermentation [34] and hydrolysis [35, 36], which increase protein digestibility, but do not modify the amino acid profile [26, 37].

The Food and Agriculture Organization of the United Nations (FAO) has proposed insects as food ingredients of the future to feed humans and animals [38]. Their use is based on the fact that insects have similar nutritional characteristics to ingredients of animal origin, in terms of protein contribution, amino acid profile, amino acid digestibility, and the presence of minerals and vitamins [39–44]. The most widely used insects worldwide for the development of food ingredients for humans and animals are black soldier fly larvae (BSFL, *Hermetia illucens*), mealworm larvae (ML, *Tenebrio molitor*), and adult house crickets (*Acheta domesticus*) [45–48], because they are produced industrially in mini-farms. From these, basic ingredients, commodities such as whole meal, defatted meal, and insect oil are obtained using simple technologies commonly used in the food industry [48–50]. However, there is great potential for obtaining other food ingredients from insects, with better sensory, and technological and even functional properties that have only been scarcely studied and have few existing industrial applications. The objective of this chapter is to analyze the potential of transforming insect flour and oil commodities into food/functional ingredients with improved sensory, technological and functional properties for massification and use as food ingredients for the future.

2. Development

2.1 Sensory barriers to the massification of insect consumption

There are several insect-based foods on the market such as cereal bars, drinks, pastas, candies, snacks, hamburgers, for human consumption [51, 52] and made with different concentrations of insect flour and oil [53–55]. The main problem lies with the acceptance of this type of food by people who are not familiar with entomophagy (insect consumption), such as people from Western cultures, who often feel disgust, perceive insects as unpleasant, and reject their consumption [56]. In several survey-type studies, it was found that insect consumption could be better accepted if "insects did not look like insects" [57–59].

People who would be willing to consume insects describe some unpleasant sensory characteristics, such as: i) unpleasant odors [60, 61], identified as smelling of fungi, algae, fishy, and earthy [62–64], ii) unpleasant tastes of fish, fungi, bitterness [65, 66], iii) dark brown color of flour causing rejection [67], iv) grainy and rough texture of flour and whole insects [62, 63], and soft and oily texture in larvae [68] (**Figure 1A and B**), and v) unpalatable appearance of whole insects (**Figure 1C**) and meals, such as BSFL meal (**Figure 1E**) [69]. Additionally, processing to convert whole larvae/insects into meal (**Figure 1D**) can worsen these sensory perceptions, as Maillard reactions occur during the thermal process [70]. These reactions alter the color, odor, and flavor of insect flours in a negative way [71] and reduce the availability of some nutrients such as vitamin B12, potassium, phosphorus, sodium, some amino acids such as lysine [66]. There is also generation of unpleasant volatiles such as aldehydes, ketones, alcohols, esters, hydrocarbons, sulfur compounds and phenols, which generate unpleasant aromas [65, 72]. Thermal processing also generates darkening; for example, fly and mealworm larvae are cream-colored with yellow and orange shades (**Figure 1A**) and the meal obtained from these is dark brown (**Figure 1E**), due to the generation of brown and black coloring pigments such as melanoidins [66, 73]. The chitinous exoskeleton of insects is resistant to crushing [74]; therefore, the flour obtained after the milling process has granular texture, due to the large particle size (1.0–1.4 mm) of insect flours [53, 75], compared with flours of plant origin for example, wheat flour, which has a small particle size of about 100–150 μm [76].

The color of insect oil varies in yellow shades, and their melting point is variable depending on the profile and fatty acid content. For example, oil from BSFL contains lauric acid as the main fatty acid (21–29% of the total fatty acids, depending on the larval diet) [77]. Lauric acid is a saturated fatty acid, which gives the oil a high melting temperature (≈ 43°C). The oil is solid at room temperature, limiting its use as a food ingredient and making the incorporation into feed and/or diet formulations complex [78]. During oil processing, negative sensory changes also occur, mainly in oils with higher polyunsaturated fatty acid content, which tend to oxidation, producing odors and flavors described as "rancid and unpleasant" [60, 61]. Crude oil contains various components such as gums, free fatty acids, aromatic residues, and pigments, which negatively affect flavor, nutritional value, appearance, and stability [79].

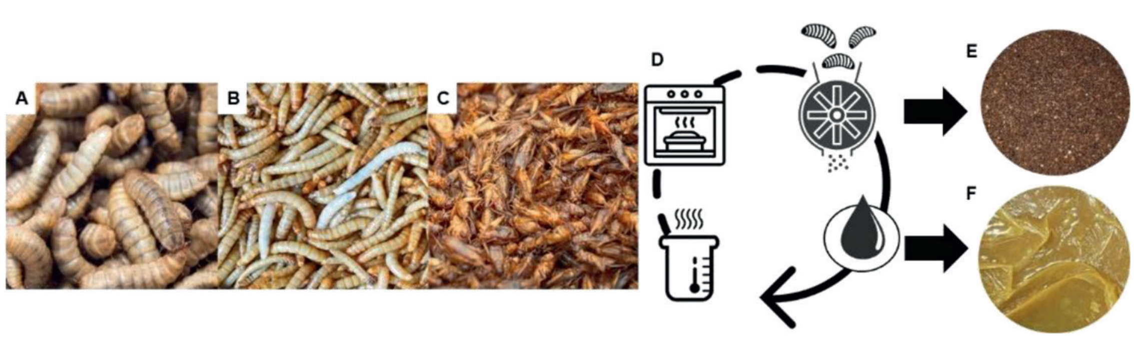


Figure 1.
Appearance of whole insects, A: BSFL, B: mealworm larvae, C: adult house crickets, D: processing of insects into food ingredients, such as flour (E) and oil (F).

The addition of whole or processed insects to a food negatively affects its sensory quality, even if added in small amounts (<5% for flour), because they contribute to characteristic flavors and aromas, considered unpalatable to people, affect the appearance and texture, and darken the product [54, 80–82]. Therefore, the addition of insect-based ingredients to foods remains a major challenge.

2.2 Common food ingredients from insects: meal and oil

The main insect-based ingredients produced in the world have been whole meal and defatted meal and oil, which are obtained by relatively simple processing and are widely used in the food industry [50]. The following processes are used to obtain flour: blanching, drying, grinding, and addition of additives [83, 84]. Blanching is the process where whole insects (larvae and/or adults) are placed in boiling water, and then removed and immersed in ice water to stop the thermal process. Blanching is used as a pretreatment to reduce the microbial load of bacteria and fungi and inactivate the degradative enzymes responsible for spoilage, but does not affect bacterial spores [85–88]. Blanching time can be from seconds to 16 minutes, with a 5-minute average, and this process can be repeated several times for differing periods of time. The ratio of insects/water used has been 1/10–1/12. The time of immersion in ice water is from 30 seconds to 5 minutes. Between the blanching and cooling processes in water, the insects can be drained and crushed. Sterilizing solutions of 5% NaCl can also be used in this process [50]. The second process the insects receive is drying to reduce total water content and water activity, decreasing degradation reactions, including enzymatic reactions and those produced by microorganisms [89, 90]. The drying methods used include air convention dryer, solar drying, oven drying, smoke drying, frying pan, freeze drying, microwave-assisted drying, fluidized bed drying, oven drying with air circulation, and ultrasound-assisted aqueous extraction. Of all these methods, the most widely used for the industrial production of insect meal is oven drying in conventional hot air drying, using temperature ranges between 40 and 80°C for 8 to 48 hours until the sample reaches constant weight [50]. The last process is milling, which mechanically reduces the whole insect to the consistency of powder or flour [91]. For grinding, the use of a roller mill [75], blade mill [92, 93], colloid mill [94], or mechanical disruptor [60] has been described with times varying between 2 and 10 minutes, depending on the method chosen [60, 93].

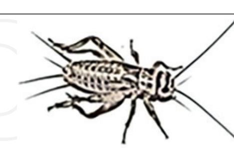
To obtain defatted meal, it is necessary to extract the oil. Oil extraction is commonly performed with organic solvents, such as hexane, ethanol, isopropanol, methanol, petroleum ether, acetone, diethyl ether, and their mixtures [94–102]. Solvent extraction techniques involve partitioning between two immiscible liquids, continuous extractions, or batch extraction of solids. This process consists of three stages: pretreatment, desolventization, and solvent refining [103]. Although extraction with organic solvents has been the most widely used for oil extraction, other methods recognized as "green" for being more innocuous have also been studied, such as extraction with supercritical CO_2 [104–106]. The latter is a promising process, with a good percentage of defatting; however, it is more expensive. High hydrostatic pressure extraction has also been investigated [107, 108]. Insect oil has been used in the formulation of human food [109, 110], salmonid diets [111, 112], complete feeds, and pet snacks [48].

The two most important nutritional components in insect meal are protein and fat. The ranges of crude protein and crude fat content of whole and defatted meal of the insects most commonly used in human food development and most consumed by animals are presented in **Table 1** [14, 94, 99, 113–120]. Of the three insects analyzed, crickets have the highest protein content in the complete meal, followed by mealworm and BSFL. The insects with the least amount of fat content in the complete meal are mealworm followed by BSFL and then crickets. Complete meal has been widely used to formulate diets for productive animals, mainly in aquaculture [121–123], pet diets and snacks [48], and human food [44, 124]. Defatted meal has a significant increase in total protein content (20–23%) and a reduction in fat content [99]. Defatted meal has been used to develop new ingredients that concentrate insect protein (hydrolysates, isolates, protein concentrates) for humans [44], specialized pet foods, such as hypoallergenic foods [48], and bioactive extracts with potential nutraceutical use [125, 126].

The protein and fat content is variable for each insect, so **Table 1** presents ranges. The primary factors influencing fat content are intrinsic variability of each insect species, developmental stage (larvae, pupae or adults), the diets used to feed the insects during the rearing and fattening period, and environmental conditions [127, 128].

2.3 Transformation of insect meal and oil into new food/functional ingredients

For mass consumption of insects to become the food of the future, it is necessary to transform insects into food ingredients of greater acceptability for the human population, using various technologies used by the food industry [129]. For animals, this is not necessary as insect meals and oil have high acceptability by aquaculture species [130], productive animals (pigs, hens, and chickens) [131–133], and domestic pets such as dogs and exotic animals [48]. **Table 2** and **Figure 2** present the new food and/or functional ingredients based on insect oil (**Figure 2A**) and meal (**Figure 1B**) commodities developed for humans. The main ingredients used as a base have been whole meal, defatted meal, and oil [172, 173]. More insect meal-based ingredients have been developed than insect oil. The developed oil-based ingredients are refined and deodorized oils, with better sensory properties (better odor and lighter yellow color). Emulsion technology has been applied to change the physical appearance of some insect oils, primarily BSFL, which as indicated above is solid at room temperature (**Figure 2A**), making it difficult to use in

Ingredients	BSFL	Mealworm	Cricket
			
Whole meal			
Protein (%)	40–43 [14]	48–57 [14]	58–69 [14]
Fat (%)	17–34 [14]	32–40 [14]	11–23 [14]
Defatted meal			
Protein (%)	46–60 [113–116]	62–71 [94, 117–119]	79–81 [99, 107]
Fat (%)	5–11 [113–116]	1–14 [94, 117–119]	1–5 [99, 107]

BSFL: Black soldier fly larvae (Hermetia Illucens), mealworm (T. molitor), cricket (A. domesticus).

Table 1.
Protein and fat ranges in dry basis of whole and defatted meal, of common insects used in human and animal feed.

Insect	Technology	New ingredient	Properties
From insect oil			
BSFL[79, 134]	Oil purification	Refined oil	Reduction of oil viscosity, turbidity and density Oil with high oxidative stability and better quality
ML[110]	Oil deodorization	Deodorized oil	Improvement of the organoleptic properties of the oil, such as appearance, color, and odor
ML[135]	Oleogelation with waxes	Oleogel as solid fat replacer in cookies	The replacement with carnauba wax/insect oleogel showed a desirable cookie quality in terms of spreadability and texture properties
BSFL[136]	Homogenization	Fat emulsions	Emulsions showed twofold lower consistency compared to the lecithin solutions of the same concentration
BSFL[137, 138]	Pre-homogenization and ultrasonication	Nanoemulsions	Nanoemulsions with high value-added for several applications in food industry Applications as drug delivery vehicles
BSFL, BM[139]	Solvent extraction	Oils with antimicrobial activity	Antimicrobial activity against *B. subtilis* and *S. aureus*
BSFL[140–145]	Solvent extraction	Lauric acid	Reduction of *E. coli*, *Streptococcus* spp., *Yersinia enterocolitica* and *Enterobacteriaceae* Increased number of *Lactobacillus* and *Bifidobacteriu.* Higher concentrations of total volatile fatty acids. Reduction of cytokine (IL-10 and 6) Positive effect on the gut microbiota composition and intestinal morphology
From insect meal			
AD, BSFL, ML, SG, AM[92, 95, 101, 146]	Alkaline solubilization and isoelectric precipitation	Protein concentrates	Lighter colored powders (beige-brown) were obtained High protein content (62–85%) Better aroma and appearance
ML, AL[147, 148]	Alkaline extraction, acid precipitation and salting out procedures	Protein isolates	Higher protein content (65–87%). Similar total amino acid content Better technological properties
AD, ML[64, 149, 150]	Biological and enzymatic hydrolysis and high hydrostatic pressures	Protein hydrolysates	Enhanced flavor (by hydrolysis and Maillard reaction) Lower chitin content obtaining antimicrobial substances Good sensory properties

Insect	**Technology**	**New ingredient**	**Properties**
MB, SB[151]	Acid/alkaline/water extraction	Gelatin	Very good gelling ability
ML, ADI, PB[152]	Homogenization of larvae with pork fat and freezing	Emulsions as meat replacement	ML was the most suitable candidate for use as a meat replacement due to its physicochemical and rheological properties
ML[153]	Extrusion	Snack	Extrusion improved the digestibility of ML proteins and starch Snacks with 10% YLM meal showed good expansion properties and pore structure, obtaining acceptable textural qualities; at 20%, the snacks showed poor expansion properties due to the higher fat content
BSFL[154]	Extrusion	Pellets	Extrudates of pure insect meal had the lowest water absorption index and the highest water solubility index. Insect meal in the corn blends negatively affected the pasting properties of the extrudates
HFL[155]	Spray drying	Micro-powder	Better appearance, similar to meals of vegetable origin Reduced emission of volatile compounds. Smaller particle size (9 μm) than other insect meals (355–1400 μm) [53, 75] Low protein content (5.1% db)
HFL[156]	Ionic gelation	Beads	Black "caviar" looking beads, darkening the color of HFL meal. Low protein content (27%) compared with HFL meal (54%) High antioxidant capacity of 1235–6903 μmol TE/100 g
AD, ML[157–159]	Yeast/lactic acid fermentation	Fermented powder	Flavor was improved The intensity of indole, pyrazines, 1-octen-3-ol and 3-octanol, which have unpleasant odors, was reduced. Pleasant volatiles, such as ethyl acetate, isopentyl acetate and 2-butanone, were increased Lactic fermentation resulted in successful acidification and increased shelf-life and safety by the control of Enterobacteria and bacterial spores

Insect	Technology	New ingredient	Properties
AD, ML, TE, OC, PB[125, 160–163]	Ultrasound-assisted extraction Pressurized liquid extraction	Functional extract	All extracts exhibited antioxidant activity and showed lipase inhibitory activity Potent hemolytic activity and anticoagulation activities
BSFL[164–166]	Solvent extraction, RNA isolation, cDNA cloning, solid-phase extraction and reverse-phase chromatography	Antimicrobial peptides (AMP)	The highest levels of AMP were induced by larvae diets supplemented with protein or sunflower oil. AMPs demonstrated activities against a spectrum of bacteria AMP exhibited antibacterial activity against both *Escherichia coli* and methicillin-resistant *Staphylococcus aureus*

BSFL: black soldier fly larvae, HFL: house fly larvae, ML: mealworm larvae, ADL: Allomyrina dichotoma larvae, AD: Acheta domesticus, BM: Bombyx mori; SG: Schistocerca gregaria; AM: Apis mellifera; AL: Anastrepha ludens; ADI: Allomyrina dichotoma; PB: Protaetia brevitarsis; TE: Teleogryllus emma; OC: Oxya chinensis; MB: Melon bug; SB: Sorghum bug.

Table 2.
New food and/or functional ingredients developed from insect meal and oil.

the formulation of diets, since it is complex to homogenize with the other ingredients and tends to form aggregates when combined with ingredients in powder form. After the emulsion process, liquid formulations are obtained (**Figure 2Ai**), with a milky appearance (**Figure 2Ai-iv**), which could be converted to powder by spray drying, to facilitate their use as a food ingredient and increase shelf life. These emulsions have been proposed as value-added ingredients for the food industry and as potential nutrient and drug vehicles for the pharmaceutical industry (in the case of nanoemulsions). Some nanoemulsions retain a milky appearance, while others tend to be transparent (**Figure 2Av**). BSFL fat has a similar fatty acid composition as coconut and palm oil, making it one of the most promising alternative fat sources for the food industry, where these lipid sources are used in a large number of processed foods [136].

The antimicrobial capacity of BSFL oil has been studied and demonstrated in *in vitro* studies against Gram-positive and Gram-negative bacteria [139, 174]. The antimicrobial capacity of BSFL is due to its high concentration of lauric acid [14]. The mechanisms of lauric acid antimicrobial processes are still being studied, but three have been described: 1) destruction of the cell membrane of gram-positive bacteria and lipid-coated viruses by physicochemical processes, 2) interference with cellular processes, such as signal transduction and transcription, and 3) destabilization of cell membranes [175], through inhibition of the enzyme MurA [176]. Very few *in vivo* investigations have been performed in animals to study the antimicrobial property of BSFL. The inclusion of BSFL oil in the diet does not affect the microbiota, improves intestinal morphology, and increases beneficial microorganism populations [140–142].

BSFL oil has the ability to regulate blood cholesterol levels due to its lauric acid content. In an *in silico* study animals fed lauric acid had increased cholesterol metabolism due to reduced HMG-CoA enzyme activity [177]. BSFL oil may also affect markers and coagulation factors, inhibiting platelet aggregation, prolonging the activated partial thromboplastin time. In *ex vivo* and *in vivo* studies, the compounds extracted

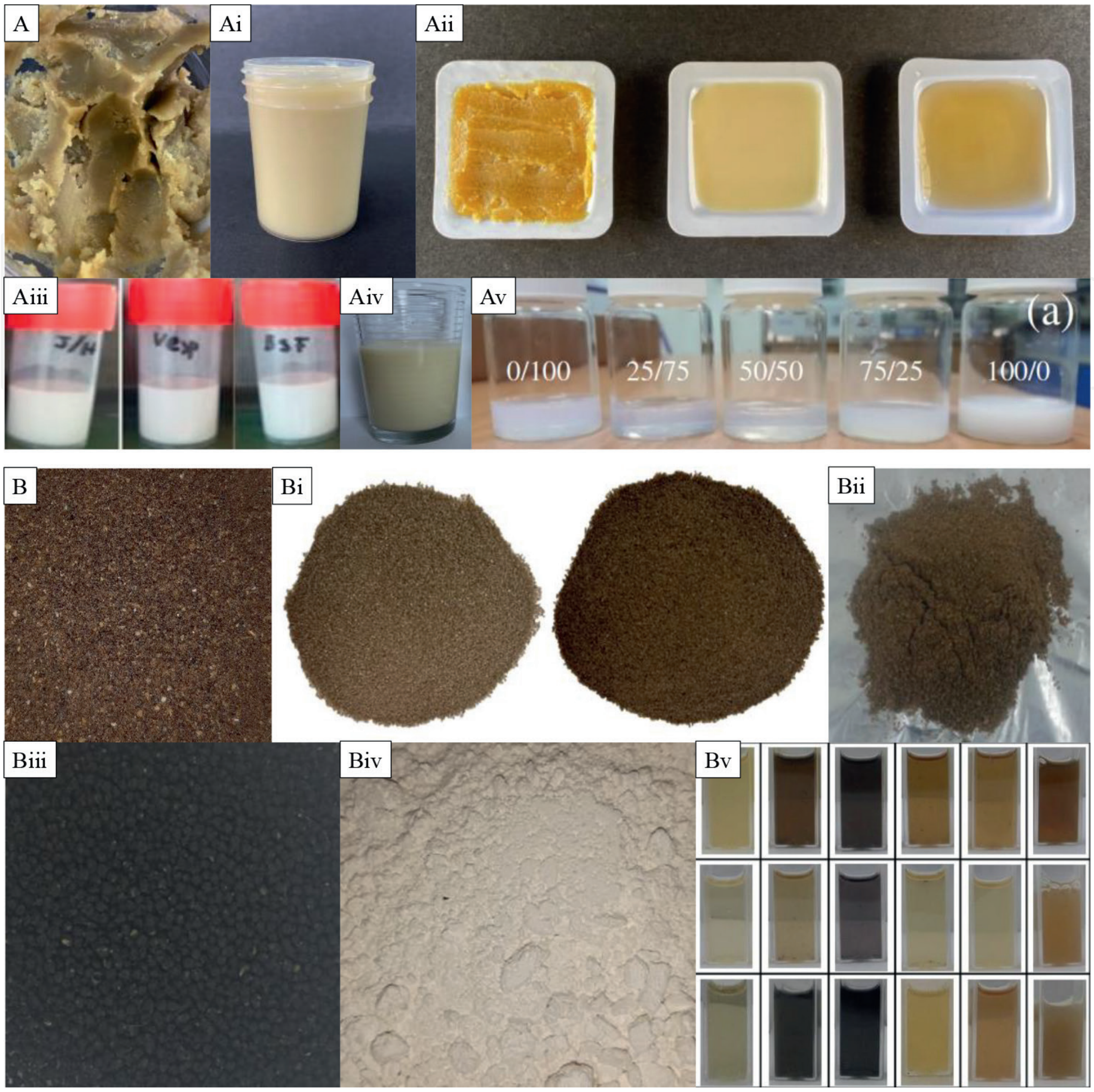


Figure 2.
Appearance of traditional insect ingredients, BSFL oil (A) and BSFL meal (B) and new insect-based ingredients, such as emulsions (Ai-Aiv [167, 168]), nanoemulsions (Av, [137]), protein extracts (Bi, [169]), protein concentrates (Bii, [170]), alginate-insect meal beads (Biii, [156]), micro-powders (Biv, [155]), and aqueous extracts (Bv, [171]).

from three insects, *Protaetia brevitarsis* seulensis, *Tenebrio mollitor* and *Oxya chinensis* sinuosa, succeeded in reducing platelet aggregation and the rate and size of arterial and pulmonary thrombus formation in mice [160–162].

Studies on new ingredients based on whole and defatted meals have focused on concentrating protein by developing protein concentrates, protein isolates, protein hydrolysates, and protein fermentates, using methods such as alkaline extraction and isoelectric precipitation (**Table 2**). The development of protein concentrates and protein isolates is focused on because i) protein is one of the most expensive nutrients in human and animal diets; and projections indicate that the price of protein ingredients of animal and plant origin will increase steadily [22]. ii) Proteins of animal origin are complex to replace in human and animal diets and are not very sustainable [178, 179]. Insect proteins represent a sustainable replacement alternative to animal proteins [180, 181]. iii) The protein content of insect meals, especially defatted meal, is very high (**Table 1**) and similar to meals of vegetable origin (40–55%), meat/bone meal (40–50%), and offal (40–60%) [182]. The protein content of defatted cricket, mealworm, and BSFL meal is similar to meals of marine origin such as fish meal (60–75%) [182]. iv) The protein quality of insects, in terms of essential amino acid content (good source of lysine, methionine, threonine, leucine, alanine, valine) and amino acid digestibility (80–93%), is excellent. v) Insect proteins tend to be high in glutamic acid, which is the main amino acid in BSFL and mealworm meal [48], and is related to umami taste, highly preferred by animals and humans [183, 184]. vi) Insect proteins have technological properties suitable for the processing of certain foods such as meat substitutes [185], jerky meat analog [186], extruded cereals [153], rusks [187], and pastas [188]. vii) Products that concentrate insect proteins as concentrates and isolates have better sensory properties than insect meals, such as lighter colors [65], better taste [64], better volatile profile [149], and better emulsifying and foaming properties [98, 102]. Insect protein concentrates and isolates have been used in human food and are commercially available. Some examples are Becrit® and Trillions®, under the concept of protein shakes; Isaac nutrition®, protein powder; AdalbaPro IPC®, protein concentrate; and AdalbaPro FTIP®, protein concentrate powder with fiber texture. **Figure 2** shows that the main change in appearance of protein concentrates (**Figure 2Bi-ii**), made from insect meals (**Figure 2B**), is a lighter coloration of the brown shades of the meals.

Hydrolysates and fermentates have been developed for the purpose of reducing some antinutritional factors of insect meals such as chitin [149], improving organoleptic properties, increasing shelf life [189, 190], providing antioxidant properties [149, 191, 192], increased nutrient digestibility, production of antimicrobial substances, and health-promoting molecules [149]. Enzymatic hydrolysis using a variety of enzymes, such as alkalase, papain, peptidase, protease; and alcalase, papain, peptidase, protease; and biological hydrolysis using yeasts (*Yarrowia lipolytica* and *Debaryomyces hansenii*) have been studied to obtain peptides with bioactive properties and to improve protein digestibility, mainly. Fermentation of insect meal with lactic acid bacteria or yeast (*Saccharomyces cerevisiae*) has been used to improve sensory properties, mainly by modifying the volatile profiles, decreasing indole, pyrazines, 1-octen-3-ol, and 3-octanol, and increasing propanol, ethanol, acetone and 2-butanone, reducing fecal, toasted, earthy, mushroom, and bitter taste [157, 158].

Other technologies applied to develop new ingredients have been extrusion to produce pellets and snacks based mainly on insect meal mixed with cereals. The main result has been the increase in the digestibility of some nutrients such as protein and starch. In these studies, it was indicated that the insect meal content used alters some important properties of the extruded products (**Table 2**). This technology has been widely used for the development of complete foods and snacks for dogs and cats [48]. Some examples are Eat Small Mindfulness®, Brit Care Immunity®, CircularPet®, Yora®, Insecta®, buggybigs®.

Encapsulation is a technology widely used in the food industry, especially spray drying [193], because it improves the sensory characteristics of the compounds to be encapsulated [194]. In addition, controlled release formulations can be developed to add the encapsulated compounds in complex foods such as yogurt, beverages, dairy, and others [195–197]. Although, this technology is widely used to improve the sensory properties of ingredients, it has not been thoroughly studied for encapsulating insect meal and oil. Among the existing works, spray drying has been used to develop insect meal micro-powders (**Figure 2Biv**), which presented better appearance and color (similar to wheat flour), better texture (with smaller particle size), and better aroma than unencapsulated house fly larvae meal (**Table 2**). However, the protein content of the micro-powders was low at about 5.1 g per 100 g of powder, whereas the meal that gave rise to the micro-powders contained 54 g of protein per 100 g of flour. Even so, micro-powders are considered a "source of protein" according to the Codex Alimentarius [198]. The challenge for this technology is to concentrate on the nutrients, especially protein, from insect meals, being able to use previously described technologies such as protein isolates and concentrates. In another study, house fly meal was encapsulated by ionic gelation, obtaining alginate-insect meal beads with an appearance similar to black "caviar" (**Figure 2Biii**), with better aroma than the unencapsulated meal (**Table 2**). The application of this type of product in human food is complex, due to the rejection that its appearance could cause, but it is possible to incorporate it as food for exotic pets (such as water turtles, fish, ferrets, hedgehogs), which consume live and dehydrated insect larvae [48]. The pet industry has a high level of innovation in food products and consumption of innovative foods and snacks is on the rise [199, 200].

In **Table 2**, the development of oil nanoemulsions is described. The technique is considered an encapsulation process, since the oil is protected and separated from the water by a dynamic surfactant layer formed by emulsifying agents. This technique has been widely used in the food industry for the following reasons: 1) to improve the stability of some lipophilic active compounds such as vitamin D3 [201], carotenoids [202], and α-tocopherol [203], 2) to improve the absorption, bioavailability, and bioactivity of lipophilic bioactive compounds with low absorption such as curcumin [204] and astaxanthin [205], and 3) to provide the ability to release encapsulated actives in a controlled manner [206, 207].

The functional properties of insect-based food ingredients, such as antioxidant capacity, antimicrobial activity, inhibition of platelet aggregation, enzymatic inhibition, and antidiabetic potential, have been less studied than their nutritional properties as food ingredients [208, 209]. The literature shows that ingredients obtained from insects such as aqueous extracts [125], meals [191, 210, 211], and proteins and peptides [126, 212, 213], exhibit high antioxidant capacity, so they could have potential use in health disorders associated with oxidative stress [214]. The antioxidant capacity is due to the presence of phenolic compounds, proteins, peptides, chitin, fatty acids, and others [215, 216].

A great diversity of bioactive compounds has been isolated from insects, such as free fatty acids, amino acids, organic acids, carbohydrates, hydrocarbons, sterols, and others [125]. The methodologies for their extraction have been ultrasound-assisted extraction (UAE) and pressurized liquid extraction (PLE), using ethanol or a mixture of ethanol and water [125] (**Table 2**). The appearance of these extracts is presented in **Figure 2Bv**, observing different colorations that depend on several factors, such as concentration of the extracts and extraction technique. Extracts have anti-inflammatory, antimicrobial, antiangiogenic, antiproliferative, and antioxidant properties. The ability to inhibit the activity of certain enzymes has also been studied. In *in vitro* studies, extracts of *A. domesticus* and *T. molitor* were able to inhibit pancreatic lipase [125]. These extracts could have an application in the treatment and prevention of obesity [217]. Proteins from the insects such as *B. mori*, *T. molitor*, *Alphitobius diaperinus*, and *Gryllus bimaculatus* [218–221] were able to inhibit angiotensin-converting enzyme (ACE), dipeptidyl peptidase-4 (DPP-IV) [220], and α-glucosidase activity [218, 221], with antidiabetic potential. In animal studies, supplementation with ethanolic extract of *B. mori* improved glycemic status in obese mice with type 2 diabetes, reducing glycemia and restoring pancreatic functionality [222, 223]. Soluble extracts obtained from 12 insect species showed antioxidant activity, the highest in extracts from grasshoppers, silkworms, and crickets [216]. Antioxidant activity was also found in aqueous extract of *Vespa affinis* L. [214]. Antibacterial substances such as N-beta-alanyl-5-S-glutathionyl-5-S-glutathionyl-3,4-dihydroxyphenylalanine from *Sarcophaga peregrina* and p-hydroxycinnamaldehyde from *Acantholyda parki* larvae were isolated from extracts of immunized insects [224, 225].

Other insect-based functional compounds extensively studied in the recent years are antimicrobial peptides (AMPs), which are extracted and purified by different technologies, such as reverse phase high-performance liquid chromatography (RP-HPLC), DNA extraction, RNA extraction, fast performance liquid chromatography (FPLC), and gel filtration chromatography [226] (**Table 2**). AMPs are peptides with low molecular weight, high thermal stability, and a broad antimicrobial spectrum [227, 228]. A large number of AMPs derived from *Acalolepta luxuriosa*, *A. mellifera*, *B. mori*, *Galleria mellonella*, *Heterometrus spinifer*, *Holotrichia diomphalia*, *Hyalophora cecropia*, *Oxysternon conspicillatum*, *Pandinus imperator*, and *Sarcophaga peregrine* have been investigated and are effective against a wide range of Gram-negative and Gram-positive bacteria [229, 230]. Their mechanism of action depends on the type of AMP and the target pathogen. AMPs can interact with the microbial membrane surface, alter permeability and induce cell lysis, enter the cell, and damage bacterial components such as DNA and RNA, and promote the bacteriostatic effects [226, 228]. The use of AMPs as an alternative to antimicrobials in human and animal health could help reduce antimicrobial resistance [228].

The challenge for the future of insects as food for humans and animals is to increase research on technologies that can be used to transform common insect-based ingredients such as meal and oil into ingredients with higher added value, functional properties, and optimal sensory properties for greater acceptance and consumption of insects by humans, so these ingredients can be included in a greater number of foods.

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Conflict of interest

The authors declare no conflict of interest.

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