Food Reviews International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lfri20

Edible Insects: Techno-functional Properties Food and Feed Applications and Biological Potential

Víctor M. Villaseñor, Jhony Navat Enriquez-Vara, Judith E. Urías-Silva & Luis Mojica

To cite this article: Víctor M. Villaseñor, Jhony Navat Enriquez-Vara, Judith E. Urías-Silva & Luis Mojica (2021): Edible Insects: Techno-functional Properties Food and Feed Applications and Biological Potential, Food Reviews International, DOI: 10.1080/87559129.2021.1890116

To link to this article: https://doi.org/10.1080/87559129.2021.1890116

Published online: 05 Mar 2021.

FOOD REVIEWS INTERNATIONAL
https://doi.org/10.1080/87559129.2021.1890116

REVIEW

Edible Insects: Techno-functional Properties Food and Feed Applications and Biological Potential

Víctor M. Villaseñor[a], Jhony Navat Enriquez-Vara[b], Judith E. Urías-Silva[a], and Luis Mojica[a]

[a]Tecnología Alimentaria, Centro De Investigación Y Asistencia En Tecnología Y Diseño Del Estado De Jalisco, A. C., Ciatej, Guadalajara, México; [b]CONACYT, Centro De Investigación Y Asistencia En Tecnología Y Diseño Del Estado De Jalisco, A. C., Ciatej, Guadalajara, México

ABSTRACT

Edible insects as an alternative protein source have gained consumers' attention, leading to new market possibilities. Several investigations have generated and characterized ingredients from insects and assessed their potential application in food, feed, and their biological potential. Insects are a rich source of protein, ranging from 30% to 65%. Insect derived ingredients show great potential to be added to food products. Protein isolates or concentrates, protein hydrolysates and peptides are obtained from edible insects using different methods. Insect protein techno-functional properties include water and oil-holding capacity, emulsifying, solubility and gelling properties. Depending on protein techno-functional properties, food applications can be designed to improve their development in the formulated food. Nowadays, several commercially available food and feed products are formulated including insect ingredients. However, research related to insect-derived peptides biological potential is limited. In-depth biological assays are needed to understand the potential health benefits of insects bioactive components. Potential future research could focus on the technological properties of insect proteins, oriented to the physicochemical interactions with food matrices, including sensory quality, texture and rheological properties of new food products.

KEYWORDS
Edible insects; protein; techno-functional properties; insect ingredients; insect biological potential

Introduction

Edible insects represent a low cost and highly available source of nutrients, principally proteins. There is an important interest in identifying new protein sources for human consumption, lately. Previous research has primarily focused on proteins from two sources: 1) animal sources, such as milk and eggs, and 2) plant sources, such as soy, pea, almond and nuts. However, in both cases, their large production is associated with high environmental impact and low production efficiency.[1]

Edible insects could be an alternative source of nutrients with low environmental impact and high-protein content (30–65%). Besides, they can be a good source of lipids (13– 33%), even fiber (5– 13.6%) and carbohydrates (4.5– 23%).[2–4] Some insect species can cause great damage to commercial crops. In México, some insect species such as Mexican grasshopper (*Sphenarium purpurascens*) have reports of affectation on corn, alfalfa, squash and bean crops, generating great costs for their eradication. Typically, chemical and biological controls are used for insect management, but the first one has a lot of unwanted effects on humans, so harvesting is considered an alternative for its control. [5,6]

Some authors indicate the benefits of insect harvesting to be decrease on required land and water, reduction of greenhouse emissions, higher feed conversions and their protein can be considered of a good quality.[6,7] Other researchers have shown concern about the growing trend in insect harvesting. For instance, the collection of fabricius (*Rhynchophorus phoenicis*) in Cameroon requires trunk

CONTACT Luis Mojica lmojica@ciatej.mx Camino Arenero 1227, El Bajío Del Arenal, Zapopan, Jalisco, México, 45019.

cuts, in this way damaging the natural ecosystem. Specific regulatory practices and regulations should be considered for maintaining the ecosystem with alterations by protecting specific areas and allowing harvesting for local people to meet protein demand.[6]

Commonly collected insects include Mexican grasshopper (*S. purpurascens*) and agave red worm (*Comadia redtenbacheri*). Other insect species can be cultivated on farms including tropical house cricket (*Grillodes sigillatus*), grasshopper (*Achetus domesticus*), mealworm (*Tenebrio molitor*) and silkworm (*Bombyx mori*).[7,8]

Different cultures have used insects as an alternative source of nutrients. Entomophagy, defined as the human practice of eating insects, has been practiced for a long time and is uncertain when it began. Evidence of this activity has been found in passages of the Bible and the Koran. It has been proposed that paleolithic humans included insects in their diets. Mesoamerican old texts and paintings show that insect consumption was linked with royalty and insects were used as a tribute to Aztec emperors.[3,8,9]

Nowadays, people from some regions in Africa, Asia and America include edible insects as part of their regular diet. They are considered a rich source of nutrients, such as proteins and lipids. Approximately 2000 different insect species are considered edible around the world. America, followed by Asia and Africa, is the region with the highest number of edible insect species. Commonly consumed insects include Coleoptera (bugs), Lepidoptera (worms) and Orthoptera (crickets).[8,10]

In some regions of Mexico, edible insect consumption is a practice of native Mexicans that continues to actual times. It includes white agave worm (*Aegiale hesperiaris*), red agave worm (*Comadia redtenbacheri*), "escamoles" *(Liometopum apiculatum*), "chapulines" (*Sphenarium purpurascens*) and "chicatana" (*Atta mexicana*). Moreover, in Mexico, edible insects can be found either on street markets or gourmet restaurants.[3,11–13]

People from rural areas of Thailand include insects such as beetles in their regular diet. However, there are reports of 194 edible insect species in this country. There is evidence that China had consumed insects since ancient times, and they have documented 324 edible species. In China, insects are used in traditional medicine and consumed directly as regular food or transformed into ingredients.[14–16]

Even though several cultures have consumed insects in the past, nowadays, most Western societies are not comfortable consuming insects. Research studies have found that people associate insects with disease carriers, unhealthy and source of pathogens.[10,17–23] Other studies have researched the willingness of people from different countries to try foods with insect ingredients. For instance, Castro & Chambers (2018) found that countries with a history of entomophagy were the most willing to try insect-based foods, such as Mexico, Peru and China. On the other hand, people from countries such as India and Japan considered insect consumption a health problem, especially linked to allergic reactions.[24] Research shows that men are more willing to try whole-edible insects and their flours in several countries than women. Also, the most disgusting and offensive insects as food ingredients are cockroaches.[10,24] Besides, studies show that consumers are comfortable eating insects when they are included as powder ingredients in conventional food matrices.[25] Tan et al. (2017) related the type of food with the adequate insect incorporation, concluding that a correct food application, such as meat products, could be an acceptable way to introduce insect ingredients in food matrices.[26] Most researchers in the field agree that better knowledge of insects by consumers and a more encouraging regulatory framework for insect ingredients can lead to an optimistic scenario for increasing insect consumption.[27–29]

The most studied insect applications in food are meat products due to their sensory characteristics. Sausage-type products are strongly flavored, which allows adding insect-based ingredients, masking their remnant off-flavors. However, other applications have been explored including snacks, cookies, bakery products and food supplements.[30,31] Besides food ingredients, edible insects have been widely used for animal feed. The addition of edible insects to animal feed formulations is economically viable due to insect low-cost production and fast growth rate.[4,7,15]

Techno-functional properties of high-protein ingredients, such as water-holding capacity (WHC) and oil-holding capacity (OHC), are important attributes considered during food formulation. Mealworm (*T. molitor*) and black soldier fly (*H. illucens*) flours present high WHC and OHC. They could be used as an alternative to vegetable flours in food products.[32] Furthermore, insect proteins from silkworm (*B. mori*) and mealworm (*T. molitor*) have been reported to exert antidiabetic and antioxidant potential using *in silico* and biochemical assays.[33,34]

Companies around the world commercialize edible insects as complete insects and flours. However, it is also common to incorporate them as ingredients in food matrices such as food bars and snacks. Scarce information regarding the role of insect ingredients in food formulations and potential health benefits is available. The objective of this review was to highlight the importance of edible insects as an alternative source of proteins. The techno-functional properties of insect proteins and flours, protein extraction methods and insect ingredient applications are discussed in this work. Besides, food and feed commercial application and potential health benefits of edible insects bioactive components are addressed.

Insect protein extraction

Insect processing is a new field in food science. There is a need to develop proper methodologies for insect protein and oil extraction. Several scientific publications report different methods for insect flours production, they could be summarized in four steps including drying, defatting, milling and sieving. Once insect flours are obtained, they can be used directly as an ingredient in food formulations or in the production of insect protein concentrates or protein isolates.[14,24,32,35–38]

Several authors have reported methodologies for insect protein extraction aiming to generate protein concentrates and protein isolates (Table 1), which are similar to reported plant protein extraction methods.[42,47,48] Insect protein extraction begins with a drying and milling step to obtain flours, followed by a defatting step, then protein solubilization, mechanical separation of insoluble fractions, protein precipitation using the isoelectric point (pI) method and drying.[14,24,25,32,35,37,38,41,49]

Defatting insect flour is an important step towards achieving the highest protein extraction yield. It has been reported that non-defatted flours presented problems during processing. Furthermore, fat interacts with hydrophobic amino acids diminishing their techno-functional properties, such as the oil-holding capacity, and emulsifying properties.[32]

Commonly used methods for insect flour defatting require the use of solvents; hexane is considered to be the first alternative due to its high fat removal capacity (>90%).[32,35,42,44] Green solvents have been used for insect lipid extraction, due to environmental safety and health issues associated with organic solvents. Zhao et al. (2016) reported that ethanol in a 5:1 ratio presented similar defatting efficiency compared to other solvents.[37] Also, Gould et al. (2018) showed that ethanol is a good alternative for complete lipid removal.[45] Ethanol is considered GRAS and has a lower environmental impact and toxicological risk compared to other organic solvents, such as hexane, heptane, and isopropanol.[37]

Alkaline pH has proved to be the most reliable protein extraction method. The defatted insect flour is solubilized in a ratio ranging from 6:1 to 20:1 (v/w), with pH ranging from 9.0 to 11.0 and a final step of drying.[37,38,44] Purschke et al. (2018) obtained a protein yield of 51.7% after an alkaline extraction at pH 9.0 for *L. migratoria*.[41] In the case of *T. molitor*, a 65% of protein dry base (DB) and 59% of yield were obtained after treatments at pH 10.5 and centrifugation at 8,850 rpm. Zhao et al. (2016) obtained 70% of protein recovery using a 0.3 M NaOH (13:1) (v/w), heating at 50°C for 75 min.[37] Mintah et al. (2020) evaluated the effect on the sample/solvent ratio for *Hermetia illucen* protein extraction they found that 20:1 (v/w) ratio presented the highest protein solubility. Furthermore, they concluded that an increase in the solvent ratio leads to lower protein extraction.[46] After the protein extraction with higher pH values, in most cases, a decrease in pH is performed to precipitate them and easily remove the media in which it is solubilized.[37,44,50]

Table 1. Edible insect protein extraction and techno-functionality.

Insect species	Extraction Method	Protein Recovery	Evaluated properties	Reference
Zophobas morio (Coleoptera: Tenebrionidae)	Protein precipitation with ascorbic acid, centrifugation and freeze-dried	88.10%	Foamability and foam stability, gel formation	[39]
Alphitobius diaperinus (Coleoptera: Tenebrionidae)		91.80%		
Acheta domesticus (Orthoptera: Gryllidae)		89.50%		
Blaptica dubia (Blattodea: Blaberidae)		86.50%		
Locusta migratoria (Orthoptera: Acrididae)	Fat extraction, protein extraction, filtration and freeze-dried	82.30%	Protein solubility, emulsifying activity, foamability and foam stability, gelation properties	[40]
Gryllodes sigillatus (Orthoptera: Gryllidae)	Alkaline extraction (pH 11), centrifugation, precipitation at the isoelectric point, centrifugation, wash and freeze-dried	ND	Solubility, water holding capacity, oil holding capacity, foaming properties, emulsifying properties	[38]
Schistocerca gregaria (Orthoptera: Acrididae)		ND		
Tenebrio molitor (Coleoptera: Tenebrionidae)		ND		
Schizaphis graminum (Hemiptera: Aphididae)	***TCA-acetone:*** *Solvent mixing, freezing precipitation, washing with acetone, drying*	20.4 mg/g	Electrophoresis (1-D, 2-D)	[24]
	Phenol: *Mixing with extraction buffer, extraction in phenol, precipitation in solvents, washing, drying*	7.3 mg/g		
	Multidetergent: *Mixing with Urea and detergents, centrifuged, precipitate with solvents, washing, and drying*	4.79 mg/g		
Tenebrio molitor (Coleoptera: Tenebrionidae)	Extracted at different pHs (7.0– 10.5) the mealworm larvae powder was centrifuged. Soluble proteins were manually separated and freeze-dried.	65 g/100 g dry base	Protein contentProtein recovery	[41]
Locusta migratoria (Orthoptera: Acrididae)	Powder (Migratory locust protein flour) was purchased and treated enzymatically (proteases)	ND	Protein solubility, emulsifying activity, foamability and foam stability, water and oil binding capacity	[42]
Hermetica illucens (Diptera: Stratiomyidae)	Frozen insect was milled, defatted with hexane and aqueous extraction (distilled water) and centrifugation were performed twice and the precipitated was freeze-dried	ND	Water and oil binding capacity, emulsifying capacity and protein solubility	[32]
Tenebrio molitor (Coleoptera: Tenebrionidae)		21%		
Tenebrio molitor (Coleoptera: Tenebrionidae)	Insect powder was defatted with hexane (12– 48 h) and protein extraction was performed by sonication.	28%	Yield of defatting and sonication	[35]
Gryllus bimaculatus (Orthoptera: Gryllidae)		34%		
Bombyx mori (L epidoptera:Bombycidae)		94%		
Gryllodes sigillatus (Orthoptera: Gryllidae)	Thawed crickets were washed with water, homogenized, pasteurized, pH adjusted, and enzymatically hydrolyzed, then heated, cooled and freeze-dried	5.2– 11.7%	SDS-PAGE, degree of hydrolysis, protein solubility, foamability and foam stability, emulsifying properties	[25]

(*Continued*)

Table 1. (Continued).

Insect species	Extraction Method	Protein Recovery	Evaluated properties	Reference
Tenebrio molitor (Coleoptera: Tenebrionidae)	Freeze-dried insects were defatted with ethanol, its protein extracted at alkaline conditions, centrifuged, pH adjusted (4.3– 4.5), washed, centrifuged and freeze-dried	70%	Water and fat absorption capacity, protein solubility, microstructure	[37]
Anastrepha ludens (Diptera: Tephritidae)	Fresh larvae were grounded at low temperature, dispersed in water, pH adjusted to 5, centrifuged and filtered	Larvae (100%), Concentrate (68.2%), Isolate (48.5%)	Protein solubility, emulsifying and foaming capacity	[43]
Coridius viduatus (Heteroptera: Dinidoridae) *Agonoscelis versicoloratus* (Heteroptera: Pentatomida)	1. Mild acid and distilled water. 2. Distilled water and alkali pretreatment. 3. Hot water and alkali treatment	C. viduatus (3%) A. pubescens (3.04%)	Viscoelastic properties of gelatin	[44]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Lyophilized powder was ground, and lipids removal was performed with ethanol, then protein fraction was dispersed in NaOH (0.25 M), incubated, centrifuged, pH adjusted (4.3– 4.5), centrifuged, washed and freeze-dried	46 ± 3%	Interfacial tension, emulsion stability	[45]
Hermetica illucens (Diptera: Stratiomyidae)	Larvae was dried by microwave and defatted with ethanol, the protein extraction was performed by solubilization in NaOH (0.25 M) and heated at different temperatures, centrifugated, washed and freeze dried.	47.68– 63.93%	Amino acid content, protein content, color, bulk density, water and oil holding capacities, nitrogen solubility, foaming properties and intrinsic fluorescence.	[46]

ND (Not declared)

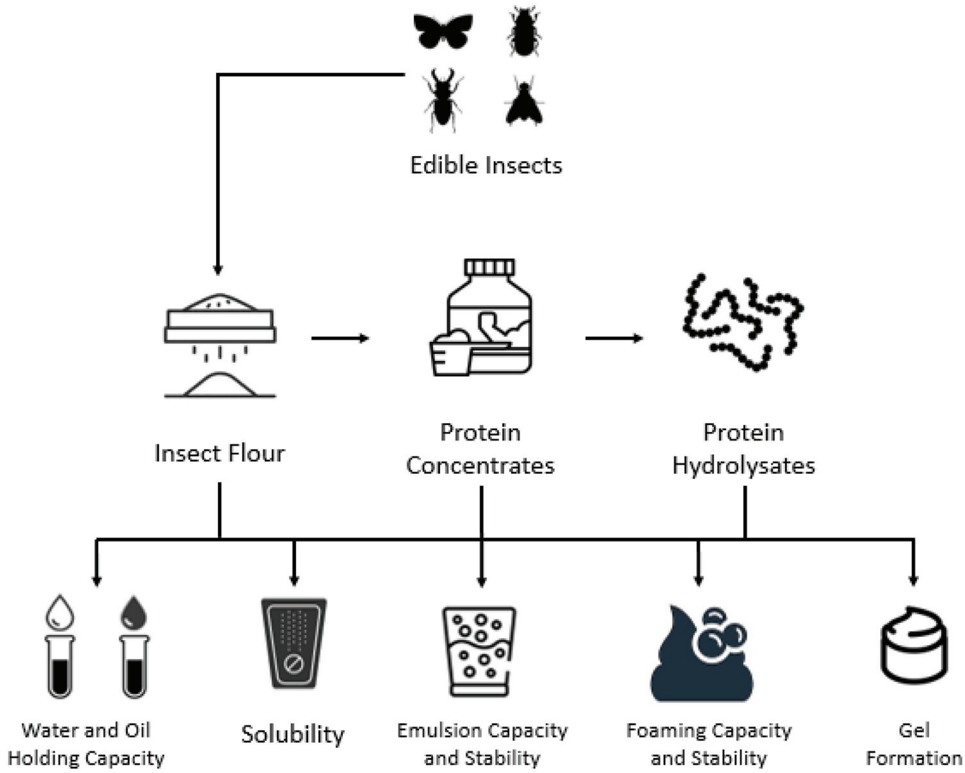

Figure 1. Techno-functional properties of edible commonly used edible insect-derived ingredients.

Alkaline extraction methods show high suitability for industrial scaling, due to the availability and low cost of basic agents such as NaOH.

Other methods such as precipitation using solvents and detergents showed low protein recovery and further studies are needed to evaluate their feasibility. Some authors have reported the use of ultrasound-assisted extraction of insect matrices for protein solubility. The results showed an improvement in protein extraction; however, more research must be performed to optimize protein conditions for maximum protein yield.[24,35,44]

Some authors have researched protein composition of edible insects. For instance, Bubler *et al.* (2016) evaluate the effect of different extraction methods on protein composition. It was found that an increase in extraction pH significantly affected the low molecular weight proteins obtained (98.9%). It was suggested that extreme conditions, such as high pH and the use of solvents (i.e. hexane), can lead to a partial and even complete proteolysis.[32]

Ten fractions were obtained of *T. molitor*, from 10 to 250 kDa SDS-PAGE bands. In this study, it was suggested that low-molecular-weight bands could be from cuticle proteins, chymotrypsin-like proteinases, other enzymes, B-glycosidase, among others. Higher molecular weight proteins could be linked to vitellogenin-like protein.[32]

Another study related the extraction method with the protein profile obtained in the wheat aphid, *Schizaphis graminum*. The most suitable alternatives for protein extraction and characterization were obtained with TCA-acetone and multidetergente methods. A wide molecular weight profile was found, with values ranging from 6.5 to over 200 kDa.[24]

Crickets have been studied likewise. A research showed that tropical house cricket (*G. sigillatus*) has proteins of different molecular weight, ranging from 14.4 to 212 kDa. On the other side, protein hydrolyzates of the same insect showed low molecular weight bands in SDS-PAGE tests; indicating that alcase is an adequate option for successful hydrolysis.[25] Other researchers have indicated that a combination of proteases (papain, Flavourzyme, Neutrase and Alcalase) with longer hydrolysis times can lead to a higher quantity of low-molecular-weight proteins. This can even be related to an increase in solubility, due to the interaction of exposed amino acids to the media.[42]

Previously, Purschkle, *et al.* (2018) obtained the molecular weight protein profile of *L. migratoria*. The protein size ranged from <6 kDa to 100 kDa. In the same work, the authors found tubulin peptide fragments and Tropomyosin.[40] These results were similar to the ones obtained for *T. molitor*, which also reported tropomyosin. This protein is responsible for allergic reactions in crustaceans.[51]

Insect protein identification has been scarcely studied, and an adequate recognition of specific proteins can lead to a better understanding of their future food and feed applications.

Techno-functional properties

Techno-functional properties of proteins are important during food formulation or traditional ingredients substitution. In the case of edible insect proteins, few studies are available compared to traditional protein sources, such as plant proteins, due to the differences in methodologies and aims of the researches. However, some of the most studied edible insect protein techno-functional properties are solubility, emulsion capacity and stability, foamability, gel formation, water-holding capacity and oil-holding capacity (Fig. 1). [25,32,37,42,49] Solubility is an important attribute in beverages and food powders. Good emulsion capacity and stability are ideal for the meat industry; sausage formulation uses strong emulsifiers to avoid water losses. Foaming is an important characteristic for desserts and shakes. Appropriate matrix formation as a gel is necessary for dairy products such as cheese or cream to obtain the right texture and reduce syneresis.[52] The understanding of the techno-functional properties of insect proteins is important to promote their incorporation in a wider range of food products.

Protein solubility

Protein solubility is a critical functional property during food processing and new product development. Solubility refers to the arrangement of polar and non-polar groups of the protein allowing them to interact with water molecules and remains in solution.[25,53] Different factors affect the solubility of insect proteins including pH, salt concentration and the amino acid composition.[42] Insect flours, such as grasshopper (*A. domesticus*) and yellow mealworm (*T. molitor*) are highly soluble at pH 9.0 and 10.0, respectively. Furthermore, their isoelectric points were reported at pH 3.0 and 4.0, respectively. Similar behavior has been reported in pea protein, with low solubility near the isoelectric point and higher solubility at higher pH, such as 8 and 9[32,52]

Insect protein products and flours show similar solubility behavior compared to plant proteins, increasing their solubility at alkaline pH compared to acidic pH. This is due to the high concentration of acidic amino acids of insect proteins.[42] The solubility of yellow mealworm (*T. molitor*) and black soldier fly (*H. illucens*) flours has been reported at different conditions and pH, ranging from 3% to 95%.[32] Mexican fruit fly (*Anastrepha ludens*) protein concentrate showed a minimum solubility at pH 5.0 (8%) and a maximum solubility at pH 10.0 (95%) which is consistent with other edible insect proteins.[43] Migratory locust (*Locusta migratoria*) protein concentrate did not follow typical protein solubility behavior. Its solubility decreased at alkaline pH, and this behavior has been reported in proteins with a heterogeneous amino acid profile.[40] Compared to common proteins, such as soy (~40%) and bean protein concentrates (70–80%), it is found that some edible insect proteins can lead to a higher solubility if an adequate extraction method is performed.[1]

Protein hydrolysis is an important process that increases protein solubility. The reduction of the protein molecular weight during the production of protein hydrolysates and peptides increases protein solubility. Hydrolysates of tropical banded cricket (*Gryllodes sigillatus*) showed an increase in protein solubility due to the unfolding of the protein and the exposure of hydrophilic functional groups.

Likewise, an increment in protein solubility was observed after the hydrolysis of *G. sigillatus* proteins. The increase in solubility from 20% to 55% could be attributed to functional groups of protein fractions and peptides that were able to interact with water molecules.[25,41]

Water and oil-holding capacity

The water-holding capacity (WHC) is the amount of water that can be absorbed by food polymers (i.e. proteins and carbohydrates). This can be influenced by various factors, such as amino acid profile, protein conformation, hydrophobicity, pH, temperature, protein concentration, among others.[54] *T. molitor* flours and protein isolates are the most studied insect-based ingredients. Several authors have reported WHC values ranging from 0.8 g/g to 3.95 g/g.[32,37,38] Similar results have been reported for *B. mori* flours and protein isolates (Zielińska et al., 2018).[38] This research group concluded that due to differences in protein profile, each insect protein should be evaluated individually. Yellow mealworm (*T. molitor)* protein isolate WHC (3.95 g/g) was higher compared to insect flour (1.29 g/g). Other insects such as desert locust (*Schistocerca gregaria)* present similar WHC in protein isolates and flours (2.18 and 2.31 g/g, respectively).[38] Nevertheless, plant proteins seem to still have higher WHC values compared to insects, with results from studies from 1.5 to 6 g/g.[1]

Insect protein hydrolysates exert good water-holding capacity; this could be due to water molecules that interact with the hydrophilic amino acid residues of the proteins. Also, it is being reported that flours have greater WHC compared to protein concentrates. *T. molitor* flour presented higher WHC (0.8 g/g) compared to its protein concentrate (0.4 g/g). This could be due to the effect of carbohydrates and other polymers on insect flours.[32,41]

The oil-holding capacity (OHC) is described as the physical entrapment of lipids in the food polymers (proteins and carbohydrates) and it is affected by the concentration of non-polar or hydrophobic amino acids present in the protein chain.[37,38] Insect protein concentrates, protein isolates and flours present different OHC. *B. mori* flour OHC ranged from 2.5 to 2.8 g/g. *T. molitor* presented an OHC of 1.71 g/g for insect flour and 3.95 g/g for insect protein isolate.[38,44] Similarly, Bubler et al. (2016) reported that protein isolates of *T. molitor* presented higher OHC compared to insect flours and defatted flours.[32] Enzymatic treatments have been shown to enhance the OHC. For instance, *T. molitor* presented an OHC of 2.33 g/g after enzymatic hydrolysis.[48]

Plant proteins have lower OHC compared to insect proteins, as the obtained values for the first ones range from 1 to 2 g/g compared to some insects, such as *T. molitor* with OHC of 2–4 g/g.[1,37,44] This behavior can be attributed to the amino acid composition of each specie.

Emulsion capacity

The emulsion capacity (EC) is the maximum amount of lipids that can be linked to an amphiphilic molecule under certain conditions. In the case of proteins, the ratio between hydrophilic and hydrophobic amino acids and the secondary structure of the protein are key factors for EC. The exposure of hydrophobic amino acids after protein denaturation allows their interaction with lipid molecules, enhancing its EC.[32,40] Protein hydrolysis using enzymatic treatments (Alcalase®, papain, Neutrase®) improves the emulsion capacity. *L. migratoria* protein increased their EC after enzymatic hydrolysis. The increment in EC was due to the breakdown of large protein molecules and the exposure of the hydrophobic amino acids.[40] Also, tropical banded cricket (*G. sigillatus*) protein after enzymatic cleavage leads to a higher EC (27–32%).[45] Protein hydrolysis must be controlled because when it is excessive, emulsifying properties are reduced, due to interfacial absorptivity and new molecular rearrangements of the generated protein fractions and peptides.[40]

pH is one of the most important parameters for emulsion capacity of proteins. Also, ionic strength, temperature, protein concentration and proportion of amino acids affect considerably this functional property. In the case of *L. migratoria*, the highest EC (55.19%) was observed at pH 5.0 and 3% NaCl. At different NaCl concentrations, insect flours and protein isolates showed high emulsion capacity and stability (up to 50%). *T. molitor* flours and protein showed EC values ranging from 65% to 66%, respectively.[41] Other insects, such as *L. migratoria* presented a wide range of EC which ranged from 7.5 to 55% in a pH-dependent manner.[40,42] In general, insect protein isolates present high EC; however, some insect proteins, such as *A. ludens* (Mexican fruit fly larvae), did not present EC properties. This could be due to amino acid composition and protein structure.[14]

Foamability

The foam formation mechanism involves the migration, unfolding, and reorganization of molecules at the air–water interface to reduce surface tension.[25,49] The importance of foamability is associated with its potential to improve texture, consistency, and appearance of foods.[37] Some of the factors that affect foam formation are protein surface hydrophobicity, specifically the presence of thiol groups and hydrophobic amino acids. Amphiphilicity is required in a protein to exert good foaming properties. *L. migratoria* flours showed no foam formation at acidic pH (<3.0) compared to pH 5.0 which presented the highest foam formation (200%). Protein hydrolysis and pH around 5.0 favors foam formation due to small peptides interactions. However, this property was improved at alkaline pH, this could be due to repulsive forces generated at pH higher than the protein pI.[42]

Other insects, such as *Zophobas morio* formed foams at different pH (3.0, 7.0 and 10.0) with a stability of 6 min. *A. domesticus* formed foams at pH 3.0 and *Blaptica dubia* at pH 5.0. Acidic pH promotes foam formation in some edible insect proteins; however, pH close to pI neutralizes the charge of some of the amino acid residues, decreasing the foam formation.[39]

Tropical banded cricket (*G. sigillatus)* protein hydrolysates prepared using a 0.5% E/S ratio (Alcalase, 30 min) presented a higher foaming capacity (155%) compared to a non-hydrolyzed control. This insect protein showed higher foaming capacity compared to other insect proteins such as pallid emperor moth (*Cirina forda)*. However, the foam stability among treatments showed a reduction of 60% after 60 min.[17]

Gel formation

The gelation capacity is a measurement of the protein's ability to aggregate and form a gel, primarily due to disulfide bonds and hydrophobic interactions. The primary factors affecting gelation capacity are protein concentration, pH, ionic strength, processing, and protein denaturation.[39,40]

Limited investigation on edible insects gelling properties has been performed, mainly using protein concentrates. Yi et al. (2013) studied different edible insect protein concentrates and indicated that at low protein concentration (<3%) it was not possible to form a gel.[39] However, protein concentrations of up to 30% at neutral and alkaline pH formed gels for yellow mealworm (*T. molitor)*, at lower levels for mealworm (*A. diaperinus)*, superworm (*Z. morio)*, house cricket (*A. domesticus)* and orange-spotted roach (*B. dubia)*. Moreover, the authors reported that acid conditions were not favorable to form gels due to the closeness to the protein pI. Under these conditions, aggregates are formed upon denaturation as a result of weak electrostatic interactions between proteins. On the other hand, at alkaline pH gels are easily formed with low protein concentration. For *L. migratoria* at pH 7.2, gels were formed at 4% and 20% of protein concentration.[40] Proteins with good gel formation capacity are important during food product development in the replacement of traditionally used proteins in food formulations.

Insect-based food applications

New food trends include sustainable sources of protein for food applications. Edible insects could be a good alternative due to their low environmental impact, the reduced space required for growth. Also, insect harvesting from crops could help to diminish some farmer's economic problems.[5,8]

Table 2. Insect-based applications in the food industry.

Insect	Application	Other Ingredients	Evaluated Parameters	Reference
Tenebrio molitor (Coleoptera: Tenebrionidae)	Extruded snacks	Wheat flour	Nutritional analysis, microstructure, texture, simulation gastrointestinal digestion	[65]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Fermented Seasoning Sauce	Toasted rice flour, koji (*Aspergillus oryzae*)	Proximate analysis, color, browning, sensory analysis	[66]
Nauphoeta cinerea (Blattodea: Blaberidae)	Wheat Bread	Wheat flour, sucrose, yeast, vegetable fat, water.	Proximate analysis, crumb hardness, crumb color, sensory evaluation	[43]
Acheta domesticus (Orthoptera: Gryllidae)	Meat emulsion	Lean pork, fatback, ice	Chemical composition, technological properties (pH, protein solubility, cooking yield, and texture)	[67]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Frankfurters	Pork ham, fatback, ice	Proximate composition, cooking loss, color, emulsion stability, protein solubility, texture, sensory evaluation	[68]
Sphenarium purpurascens (Orthoptera: Pyrgomorphidae)	Extruded snacks	Corn flour	Water holding capacity, oil holding capacity	[69]
Bombyx mori (Lepidoptera: Bombycidae)	Meat batter	Pork lean meat, fatback	Proximate analysis, color, pH, cooking loss, apparent viscosity, texture	[48]
Bombyx mori (Lepidoptera: Bombycidae)	Emulsion Sausages	Pork ham muscle, fatback	Proximate composition, pH, color, protein solubility, emulsion capacity, gel-forming capacity	[67]
Ephemeroptera Diptera Isoptera	Crackers, muffins, meatloaf, sausages	ND	Sensory analysis	[70]
Coridius viduatus (Heteroptera: Dinidoridae) *Agonoscelis versicoloratus* (Heteroptera: Pentatomida)	Ice-Cream	Ice-cream mix, milk, cream, gelatin, sugar	Sensory evaluation	[44]
Hermetica illucens (Diptera: Stratiomyidae) *Acheta domesticus* (Orthoptera: Gryllidae) *Tenebrio molitor* (Coleoptera: Tenebrionidae)	Bread	Wheat flour, salt, compressed yeast	Texture, volume, color, rheological properties	[71]

ND (Not declared)

Sensory evaluation of edible insects is an interesting topic that has been addressed lately. Some authors have described the texture of insects from soft and juicy, to hard and crispy.[55,56] And this trait depends on the insect cooking method. Caparros et al. (2016) indicate that cooking and frying achieve a crispy texture, rather than boiling cooking that promotes a juicy insect texture, which is not very palatable.

Regarding flavor, some authors have described the flavor profile of different insects. Ramos-Elorduy (1998) in her book "Creepy Crawly Cuisine: The Gourmet Guide to Edible Insects" describes categories of insects and an overall taste. For instance, ants and termites were described as sweet, almost nutty. Beetles tasted such as whole-wheat bread, cockroaches presented a mushroom flavor. Other insects such as the dragonfly were described as fishy notes and mealworms showed nutty flavor.[56] Termites flavor agrees with Nigerian reports, which reported a nutty flavor for termite (*Macrotermes nigeriensis)*.[57]

Insects, such as stinkbugs have been described with apple flavor and the African population indicated this insect has a chili flavor.[56,58] Honeybee has been evaluated and described in terms of milky, sweet and chewy savory flavors, although these traits depend on the location of the insect.[36,59] Volatile organic compounds were identified, finding that most of these molecules were odorless alkanes and alkenes, which are used as a defense mechanism.[36] Even though there are some reports on sensory evaluation of whole-edible insects, efforts must be directed to the evaluation of flavor, odor, and texture in food applications.

Insect composition includes different molecules such as proteins, lipids, carbohydrates, minerals, and fibers. Chitin, a long-chain polymer of N-acetylglucosamine, is the most usual insoluble fiber in insects and is the main component of the insects exoskeleton.[60–63] The chitin content of edible insects depends on the development stage.[8] This fiber does not present direct allergic activity but has been reported to present immune-stimulating properties that can be linked to allergic reactions if consumed at high concentrations. Besides, chitin has poor digestibility which can decrease its nutritional value.[64] In lower concentrations, it has proven to be beneficial to human health, as it acts as a prebiotic for gut bacteria.[61,63]

Several authors have evaluated the use of edible insect ingredients in food formulations, principally in meat products such as sausages (Table 2). One of the most used edible insect ingredients is the yellow mealworm flour (*Tenebrio molitor)* due to its high protein (50– 55% DB) and fat content (30–35% DB).[35,65] Also, house cricket (*A.domesticus)* was added to a meat emulsion to substitute lean pork and backfat. It showed that a replacement of 10% of backfat with the insect flour could increase the protein content and could be considered a good alternative as a non-meat-based ingredient.[67]

Other studies have reported different insect ingredients in meat products due to their strong flavor that could mask insect taste. Choi et al. (2017) used dried *T. molitor* larvae to substitute pork ham in Frankfurters.[68] Different treatments, including diverse percentages of mealworm flour, were used ranging from 5% to 30%. They reported that 10% insect substitution presented similar properties compared to pork ham, such as emulsion stability and overall acceptability compared to regular Frankfurters. Other studies showed that the addition of insect ingredients into meat-based products increased the nutritional value by increasing the protein content and showed good sensory characteristics compared to the original product.[29,68]

Research performed on the effect of edible insect ingredients over nutritional and sensory characteristics is extensive. However, the impact of ingredient substitution on techno-functional properties is scarce. Meat products, such as sausages and meat emulsions present different techno-functional behavior when fat is replaced by insect ingredients.[48,67,68]

The texture is one of the sensory attributes primarily affected by food products added with edible insect ingredients. A low concentration of insect protein ingredients (i.e. yellow mealworm powder or house cricket flour) can improve hardness and gumminess. Conversely, an increase in insect concentration from 10% up to 25% negatively affects texture parameters, increasing the chewiness due to more elasticity associated with the formation of protein networks in meat products.[48,67] Water-binding properties of meat products are also affected by the addition of insect ingredients. Insect flour

Table 3. Patents including edible insect ingredients.

Publication number	Publication Year	Title	Inventors	Edible insect
EP3262958	2018	Preparation made from Insect Larves and Method for the Production Thereof	Boeckx Hilde, *et al*	Morio worms (*Zophobias morio*), mealworms (*Tenebrio molitor*), lesser mealworms (*Alphitobius diaperinus*), wax moth (*Galleria mellonella*), silk moth (*Bombyx mori*)
CN106923059	2017	High-protein nutritive crab feed	Du Fengzhen	*Bombyx mori*
106,819,662	2017	Method for producing insect proteins and grease by efficient conversion of crop straws through multi-stage cooperation of insects	Zhen Longyu, *et al*	*Hermetia illucensTenebrio molitor*
CN106615935	2017	Traditional Chinese medicine composition used for antibiotic-free breeding of free-range chickens.	Zhou Suqing	Worm
WO2017066880	2017	Edible insect derived products and processes for the manufacture and use thereof	Lee Cadesky	Cricket (*Acheta domesticus*), mealworm (*Tenebrio molitor*), black soldier fly larvae (*Hermetia illucens*) and wax moth larvae (*Bombyx mori*).
CN106962275A	2017	Black swine culturing method	但珠明	Worms, yellow mealworm, aphids and bees
CN106901057	2017	Chicken feed prepared from mulberry pomace and preparation method thereof	Yu Huailong	Insect powder
CN106833865	2017	Non-solvent type high-efficient extracting method for energy insect lipids	Wang Cunwen, *et al*	ND
CN106819630	2017	Fish Feed	Li Liurong	Insect powder
CN106689785	2017	Palatable and disease-resisting feed for gooses	Zhang Guihe	Worm protein
CN106666144	2017	Milking sow feed containing insect powder and preparation method of milking sow feed	Yang Huansheng, *et al*	*Musca domestica, Hermetia illucens* and *Chrysomya megacephala*
CN106615628	2017	Piglet conservation feed containing insect powder and preparation method of piglet conservation feed	Yang Huansheng, *et al*	*Musca domestica, Hermetia illucens* and *Chrysomya megacephala*
CN106615800	2017	Creep feed with insect powder for piglets and method for preparing creep feed	Yang Huansheng, *et al*	*Musca domestica, Hermetia illucens* and *Chrysomya megacephala*
CN106561978	2017	Cheap snake feeding feed and fabrication method thereof	Pan Shengwen	*Tenebrio molitor*
CN106578356	2017	Animal nutrition enhancer and application thereof	Hu Wenfeng, *et al*	*Tenebrio molitor* and *Hermetia Illucens*
CN106260548	2017	Compound snake feed	Zhang Songbo	*Bombyx mori*
CN106551175	2017	Special feed for prawn culture	Yi Dajun	*Musca domestica*
CN106551188	2017	Feed capable of increasing the delicious degree of shrimp and preparation method thereof	Guo Chengli, *et al*	*Musca domestica* and stick insect
CN106260771	2017	Feed formula special for improving meat quality of fried fantail shrimps	Luo Shihua	Green insect
CN106360067	2017	Quail feed	Luo Rongjuan	*Cicada pupae*
CN106360082	2017	Feed for culturing local chickens laying insect eggs	Yu Jie, Lan Peijian	*Musca domestica, Tenebrio molitor* and red worms, snails and cockroaches
WO2017017635	2017	Feed additive, Use thereof and Method of Feeding Poultry	Damian Józefiak, *et al*	*Shellfordella lateralis, Hermetia illucens, Gryllodes sigillatus* and *Gryllus assimilis*
CN106387452	2017	Meat pigeon feed	Luo Rongjuan	Worm
KR1020160134939	2017	Feed Additive for Fish Farming Using Insects	Kang Seung-ho, *et al*	*Tenebrio molitor, Gryllus bimaculatus.*
US20170318855	2017	Method and System for Spray Drying Insects	Mott, Gabe, *et al*	ND

(*Continued*)

Table 3. (Continued).

Publication number	Publication Year	Title	Inventors	Edible insect
CN107410707	2017	Pig full-price compound feed containing insect protein and pig meat after feeding thereof	Chen Yangcheng; *et al*	*Musca domestica*
CN107348349	2017	High-protein noodles and production method thereof	Chen Wei	ND
CN106118847	2016	Method for extracting *Tenebrio molitor* oil	Dong Xiao, *et al*	*Tenebrio molitor*
CN106107127	2016	Pig feed capable of improving fragrance of pork	Cai Xisen	*Tenebrio molitor*
CN106071388	2016	Healthcare feed for finless eels	Song Fumei	Earthworm, cockroach
CN106036246	2016	Litopenaeus vannamei compound feed prepared based on conversion of hermetia illucens larvas of kitchen waste	Huang Yanhua, *et al*	*Hermetia illucens*
CN105995122	2016	Blue peafowl feed and processing method thereof	Peng Changan, *et al*	Cockroaches, grasshoppers, green worms, and grass mites
CN106173466	2016	Poultry Feed	N/A	Tenebrio molitor
CN105942197	2016	High-protein nutritious noodles and making method thereof	Gao Xueli, *et al*	Grasshoppers, cockroaches, and silkworm pupae
CN105614030	2016	Dry Pet Food	Li Zhihua	ND
CN105475660	2016	Dry Cat Food	Li Zhihua	ND
CN106174487	2016	Health food for male fertility	Su Zhaoshang	*Clanis bilineata tsingtauica*
CN106172812	2016	Preparation method of fiber health food	Su Zhaoshang	*Clanis bilineata tsingtauica*
CN106172759	2016	Health-care food for female pregnancy preparation	Su Zhaoshang	*Clanis bilineata tsingtauica*
US20150374005	2015	Method to Convert Insects or Worms into Nutrient Streams and Compositions Obtained Thereby	Tarique Arsiwalla, *et al*	*Hermetia illucens, Musca domestica, Zophobas morio, Tenebrio molitor*
RU0002557402	2015	Milk Substitute Production Method	Уланова Рузалия, *et al*	*Musca domestica, Cryptotermes domesticus, Lucilia sericata, Tenebrio molitor*
MXMX/A/2009/001344	2014	*Amaranthis hypochondriacus* adicionado con harina de *Sphenarium purpurascens Ch*. y *Glycine max* cubierto con chocolate.	Alejandro Barragán Ocaña, *et al*	*Sphenarium purpurascens*
CN101116471	2012	Edible insect albumen powder and the production process and application thereof	Chen Chen, *et al*	*Bombyx mori, Tenebrio molitor*, black mites, locusts and scorpions
US20080075818	2008	Production and processing of insects for transformation into protein meal for fish and animal diets	Ernest D. Papadoyianis, *et al*	Blattodea (roaches, cockroaches)Orthoptera (grasshoppers, locusts, katydids, crickets)Diptera (flies)Lepidoptera (moths and butterflies)
US5618574A	1997	Fish Food	Gene W. Bunch	*Musca domestica* and *Hermetia illucens*

ND (Not declared)

Table 4. Insect-based applications in feed industry.

Insect	Application	Other Ingredients	Evaluated Parameters	Reference
Hermetica illucens (Diptera: Stratiomyidae)	Meal supplement for swine	Soybean, corn, swine grease, mineral premix, vitamin premix	Proximate analysis, palatability trial, digestion trial	[73]
Hermetica illucens (Diptera: Stratiomyidae)	Feed for channel catfish and blue tilapia	Fat, poultry by-product, soybean, milled rice, distiller dried grains with solubles alfalfa, gluten, and wheat middlings	Weight gain, feed consumption, feed efficiency, mortality rate, length	[74]
Hermetica illucens (Diptera: Stratiomyidae)	Feed for European seabass	Gluten (corn, wheat), fish oil, vitamin and mineral premix, agar, soybean, binder, taurine, calcium diphosphate, cellulose	Proximate analysis, growth performance, feed efficiency, plasma metabolites, digestibility coefficients, activity of specific enzymes	[75]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Feed for European Seabass	Gluten (corn, wheat), Vitamin and mineral premix, Starch, Fish oil	Proximate analysis, Growth performance (mortality, dry matter intake, weight gain, specific growth rate, feed conversion, protein efficiency, feeding rate)	[76]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Free-range chickens meal	Corn, soybean, gluten, vitamin-mineral premix	Proximate analysis, growth performance, hematological and serum parameters	[77]
Tenebrio molitor (Coleoptera: Tenebrionidae) *Hermetica illucens* (Diptera: Stratiomyidae)	Broiler chickens meal	Maize, soybean, soybean oil, dicalcium phosphate, calcium carbonate, sodium chloride, sodium bicarbonate, vitamin, and mineral premix	Proximate analysis, apparent digestibility, apparent metabolizable, energy, amino acid apparent ileal digestibility	[78]
Tenebrio molitor (Coleoptera: Tenebrionidae)	Blackspot sea bream meal	Herring, gelatinized starch, fish oil, vitamin, and mineral premix, carboxymethylcellulose	Growth performance, morphometric analysis, organoleptic traits, proximate analysis	[57]
Hermetica illucens (Diptera: Stratiomyidae)	Rainbow trout meal	Anchovy, gluten, soybean, gem gel, fish oil, poultry fat, vitamin and mineral premix, taurine, dicalcium, phosphate, amino acids	Hepatosomatic index, intraperitoneal fat ratio, muscle ratio, muscle composition, fatty acid composition	[62]
Zonocerus variegatus L. (Orthoptera: Pyrgomorphidae)	African catfish fingerlings meal	Fish meal, groundnut cake soybean, corn, vitamin/ mineral premix, palm oil, chromic oxide, salt	Proximate analysis, growth performance, feed utilization, weight gain, mortality rate	[79]
Hermetia illucens (Diptera: Stratiomyidae)	Atlantic salmon meal	Fish meal, soy protein concentrate, wheat gluten, fish oil, rapeseed oil, Vitamin, and mineral premix	Chemical composition, growth performance, somatic index, apparent nutrient digestibility, digestive enzyme activity, total bile acids level	[80]
Hermetia illucens (Diptera: Stratiomyidae) *Acheta domesticus* (Orthoptera: Gryllidae)	Extruded aquafeed pellets	Sunflower cake, maize germ, wheat pollard, dried freshwater shrimps and dried cassava chunks	Proximate composition, floatability, expansion ratio, surface area and volume, bulk density, pellet durability index, water absorption index and water solubility index, water stability and sinking behaviour.	[81]
Hermetia illucens (Diptera: Stratiomyidae)	Fish feed formulation	Wheat flour, vitamin and mineral premix.	Proximate analysis, diameter, and floatability of pellets.	[82]

addition has been reported to increase pH in the final product compared to meat. An increment in pH in meat product formulations could increase water loss during the cooking and drying process.[48,68]

Ayieko et al. (2010) prepared different food products including crackers, muffins, meatloaf and sausages using lake flies from families Chaoboridae and Chironomidae and termites from Termitidae family. Results showed that formulation with insect flours required the incorporation of food additives to increase the product sensory characteristics. Furthermore, insect flours addition needs to be adapted depending on the product to improve the techno-functional and sensory profile. For instance, mayfly is recommended to be used on meat products due to its strong flavor.[70] Besides, using insect flours in bakery products is a common food application. Bread made with 5% of *H. illucens, A. domestica* and *T. molitor* flours showed an increase in protein and lipid content compared to wheat control. Regardless of the displeasing perception of cockroach, fortification of bread with *N. cinereal* flour showed an excellent sensory profile and good acceptance among consumers.[43,71]

Other food products such as snacks and ice-cream have been formulated with a percentage substitution of their regular ingredients with insect-based ingredients. For instance, extruded snacks using with up to 15% of *Sphenarium purpurascens* flour showed acceptable sensory characteristics and good process effectivity.[69,72] Also, *T. molitor* flour addition improved extruded snack technological properties. Microstructure, expansion and pore structure were the characteristics that presented the best results. Mariod et al. (2014) extracted gelatin of melon bug (*Coridius vidautus*) and sorghum bug (*Agonoscelis versicoloratus*) and used it as an ingredient for ice-cream production. Results showed a less appealing product compared to a commercial product.[46,65]

In extruded snacks, it is reported that the addition of insect ingredients can modify the techno-functional properties. Azzollini et al. (2018), indicated that porosity and pore size decreased with an increase in the concentration of yellow mealworm flour in the food formulation. On the other hand, Cuj-Laines et al. (2017) reported that water absorption capacity increased when Mexican grasshopper protein concentrate was added to extruded snacks. This could be due to a higher amount of proteins to interact with the water molecules.[65,69] The effect of edible insect flours on bakery products has been widely studied. However, their physicochemical and sensory characteristics are principally affected.[43,71] Water absorption capacity tends to decrease in the bakery products formulated with insect flours. Gonzalez et al. (2018) conclude that the addition of *A. domestica* and *H. illucens* flours decreased the water absorption capacity in the formulated product. This could be attributed to the particular composition of these particular insect proteins (low hydrophilic amino acids). Furthermore, bread crust color is affected by the incorporation of insect flours, for instance, darker bread is generated when adding insect flours such as *N. cinerea, A. domestica* and *H. illucens*.[43,71]

One important factor that should be taken into consideration is the adequate amino acid profile of edible insects. Ramos-Elorduy, *et al.* (1997) evaluated edible insects from Oaxaca region in Mexico, finding that the highest protein quality score was to *Hoplophorion monograma* (79%), followed by *Scyphophorus acupunctatus* (72%) and *Polistes instabilis* (72%). It was noted that this score depends on the concentration of amino acids that fulfill the requirements indicated by the World Health Organization (WHO). Interesting information regarding this study is that a large number of insects lack or contain limited concentrations of tryptophan.[2]

The incorporation of edible insect ingredients into food products as flours represents a challenge. Different studies suggest that low concentrations of insect flours could be incorporated into bakery and meat products without important sensory modifications. Higher concentrations can lead to modification of the final product sensory profile, including the color of the crust in bread and hardness and chewiness in meat products.[43,48,65,67,71] The substitution of wheat flour with gluten-free flours such as edible insect flours complicates bread and bakery product formulation.[29,43,71] Furthermore, consumers tend to dislike food products formulated with edible insect ingredients when they realize they are included in the food formulation.[29,43,67,71] This could be considered the biggest challenge to overcome in edible insect food products. More information related to edible insect importance should be diffused among consumers to increase edible insect ingredients overall acceptability.

Table 5. Commonly consumed edible insect pictures.

Common name	Scientific name	Picture	Reference
Black soldier fly	*Hermetia illucens*		[71]
House cricket	*Acheta domestica*		[71]
Mealworm	*Tenebrio molitor*		[71]
Migratory locust	*Locusta migratoria*		[86]
Silkworm	*Bombyx mori*		[26]
Mexican fruit fly	*Anastrepha ludens*		[50]

(*Continued*)

Table 5. (Continued).

Common name	Scientific name	Picture	Reference
Morio Worm/King Worm	*Zophobas morio*		[87]
Dubia roach	*Blaptica dubia*		[88]
Mexican grasshopper	*Sphenarium purpurascens*		Own picture

Due to the growing interest in edible insects and their applications, several companies and research centers have performed intensive investigations on edible insects. One clear example is the growth in patent publications using insects, according to the World Intellectual Property Organization (WIPO) (Table 3). Food applications are limited compared to feed applications; however, some products have been developed, such as a nutritive bar added with "chapulín" (*S. purpurascens)* flour or noodles enriched with protein from a mixture of insects. Companies in Mexico use grasshoppers and crickets (Orthoptera) to obtain flours and bakery products. Other enterprises in the United States are taking advantage of house cricket (*A. domesticus*) to produce complete insect snacks, flours, and protein bars.

Table 6. Biological potential of different insects.

Insect	Studied component	Bio-functionality	Assay Method	Dose	Reference
Spodoptera littoralis (Lepidoptera: Noctuidae)	2 Enzymatic hydrolyzates of insect protein vs nonhydrolyzed extract	ACE inhibitory activity	Spectrophotometric method using FAPGG as substrate. HPLC method using DTG as substrate	*B terrestris* (1.253 mg/mL)	[51]
Bombyx mori (Lepidoptera: Bombycidae)				*S. gregaria* (8.157 mg/mL)	
Schistocerca gregaria (Orthoptera: Acrididae)				*S. littoralis* (0.591 mg/mL)	
Bombus terrestris (Hymenoptera: Apidae)				*B. mori* (0.588 mg/mL)	
Hermetica illucens (Diptera: Stratiomyidae)	Clean and ground insect powder	Protein quality (food supplementation) and fermentation characteristics of their indigestible fractions	In vitro method: Simulation of the dog's digestive processes in the stomach, small and large intestine	10 g air-dry material	[85]
Musca domestica (Diptera: Muscidae)					
Tenebrio molitor (Coleoptera: Tenebrionidae)					
Acheta domesticus (Orthoptera: Gryllidae)	Thermal processing of cricket flour	Antioxidant capacity, In vitro digestibility	Antioxidant: FRAP and ORAC, In vitro digestion: Gastric bioreactor	5% of cricket flour	[28]
Bombyx mori (Lepidoptera: Bombycidae)	Peptides from enzymatically hydrolyzed male silkmoth	Antioxidant activity	ORAC and DPPH	0.08 to 0.24 mg/mL	[83]
Musca domestica (Diptera: Muscidae)	Housefly larvae protein hydrolysates	Antioxidant activity	Superoxide and hydroxyl radical scavenging activity, DPPH, reducing power and metal chelating activity	0.2– 1 mg/mL	[89]
Vespa affinis (Hymenoptera: Vespidae)	Aquous extract	Antioxidant activity	DPPH, Hydroxyl radical, superoxide radical, activities of antioxidant enzyme (rGST and rCAT). The antioxidant potential using THP-1 monocytes.	DPPH: 0.25– 6.25 mcg/mL. Hydroxyl and superoxide radical: 1.25– 15 mcg/mL Antioxidant enzymes: 1.25– 10 mcg/mL Cell culture: 0.4– 1.2 mcg/mL)	[90]

(*Continued*)

Table 6. (Continued).

Insect	Studied component	Bio-functionality	Assay Method	Dose	Reference
Blaptica dubia (Blattodea: Blaberidae)	Peptides obtained by *in vitro* gastrointestinal digestion	Antioxidant activity	ABTS and DPPH, Iron and copper chelating activity	BD: 5.21 mg/mL	[91]
Gromphadorhina portentosa (Blattodea: Blaberidae)				GP: 5.62 mg/mL	
Locusta migratoria (Orthoptera: Acrididae)				LM: 5.88 mg/mL	
Zophobas morio (Coleoptera: Tenebrionidae)				ZM: 1.88 mg/mL	
Amphiacusta annulipes (Orthoptera: Gryllidae)				AA: 1.68 mg/mL	
Tenebrio molitor (Coleoptera: Tenebrionidae)	Ethanol extract	Anti-adipogenic and antiobesity effects	Expression levels of PPAR-γ, C/EBPα with real time PCR. Expression levels of lipogenesis specific genes SREBP-1 C, LPL, SCD1 & FAS.	1 & 2 mg/mL	[92]
Bombyx mori (Lepidoptera: Bombycidae)	Silkworm pupa hydrolysate	ACE inhibitory activity	Molecular docking	IC50: 102.15 µM	[49]
Bombyx mori (Lepidoptera: Bombycidae)	Silkworm pupa hydrolysate	ACE inhibitory activity	Molecular docking	IC50: 21.7 µM	[84]
Bombyx mori (Lepidoptera: Bombycidae)	Silk Cocoon hydrolysate	Antidiabetic potential	α-Glucosidase inhibitory activity	IC50: 37.1 mg/mL	[33]
Bombyx mori (Lepidoptera: Bombycidae)	Sericin extracted from cocoons	Antioxidant activity	ABTS and DPPH	N/A	[4]

Notes: ACE (Angiotensin-I converting enzyme), **FAPGG** (3-(2-Furylacryloyl)phenylalanyl-glycyl-glycine), **DTG** (dansyltriglycine), **FRAP** (Ferric-reducing ability of plasma), **ORAC** (Oxygen Radical Absorbance Capacity), **DPPH** (2,2-diphenyl-1-picrylhydrazyl), **rGST** (recombinant glutathione S-transferase), **rCAT** (recombinant catalase) **ABTS** (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)), **PPAR-γ** (Peroxisome proliferator-activated receptor gamma), **C/EBPα** (CCAAT-enhancer-binding proteins), **PCR** (Polymerase chain reaction), **SREBP-1 C** (Sterol regulatory element-binding transcription factor 1), **LPL** (lipoprotein lipase), **SCD1** (Stearoyl-CoA desaturase-1), **FAS** (fatty acid synthase).

Insect-based feed application

The animal feed industry has used insects as an inexpensive source of protein and other nutrients. Especially, the aquaculture industry has experienced an important growth in recent years. One of the major challenges that this industry faces is the high demand for specialized feed products. Plant-based feedstuffs are becoming unsustainable resources. Besides, marine feed sources are scarce and expensive. Therefore, the use of insect ingredients could be an adequate source of nutrients for aquaculture feed (Table 4). [36,62,74–76,79,80] It is worth mentioning that most research related to the use of edible insect ingredients in feed formulations do not focus on the texture characteristics or techno-functional properties of feed products. However, good acceptance is taken into consideration when meals are formulated.[75]

Black soldier fly *(H. illucens)* larva is one of the most studied insect species as a feed ingredient. This insect is used for replacing other protein sources. Insect meal could replace up to 50% of regular ingredients without affecting fish growth or sensory quality of the fillets. For catfish and blue tilapia, a 100% larvae feed resulted in insufficient protein intake for normal growth; therefore, a 10% replacement exhibited better results compared to 100%.[4,74] European bass trials showed that inclusion of 20% to 25% of *H. illucens* and *T. molitor* powder could be used with a significant improvement in growth performance, feed utilization and digestibility.[75,76] Besides, 60% of *H. illucens* in combination with fish oil can be supplemented in Atlantic salmon diet without changes in body composition.[80]

Edible insect ingredients in feed formulation represent a good source of certain amino acids, such as alanine and arginine, compared to plant-based products. Magalhaes et al. (2017) and Belghit et al. (2018) reported that *Hermetia illucens* flour is an adequate source of essential amino acids for fish growth.[80,83] Even though edible insect ingredients have been successfully added to aquaculture feed, there are some disadvantages, such as the lack of polyunsaturated fatty acids (PUFA), which are important nutrients in fish metabolism.[57,80]

Beyond the nutritional impact of insect ingredients on fish nutrition and growth, some authors have found a reduction in cholesterol levels in some fish species. This could be due to the presence of chitin in insect ingredients. Furthermore, chitin has been shown to be an effective prebiotic material for bifidobacterium in some fish species.[75,79]

There is scarce research related to the physicochemical and techno-functional properties of insect feed. Most studies use whole insects or ground meals with little or no processing. Pellet formation is a common process to elaborate fish meals. Pellet formation process could enhance nutrients digestibility and bioavailability.[81,84] Characteristics such as floatability, moisture content, bulk density are important during aquaculture feed development. Tze et al. (2017) evaluated fish meal pellets added with black soldier fly (*H. illucens*) at 10% and 50% substitution. Pellet size and protein ratio affected floatability, bigger pellets with lower protein showed the lowest floatability.[84] Besides, extruded fish meals formulated by adding black soldier fly (*H. illucens*) and common cricket (*A. domestica*) did not present significant effect on pellet floatability, expansion rate, surface, and volume. Also, the moisture content is a very important parameter that affects feed floatability. Extruded pellets with high water content show high floatability values, expansion rate, surface area and volume.[81]

H. illucens were used in swine feed supplementation, 6% to 8% replacement of the larvae meal was recommended, contributing to the amino acid profile necessary for swine growth. Furthermore, broiler chickens have been fed with other edible insects, such as *T. molitor* and *H. illucens* due to their digestible amino acid content, showing no negative effect on their productive performance or morphological features.[64,77,78] On the other hand, Bosch et al. (2016) obtained the amino acid profile for black soldier fly (*H. illucens*), housefly (*M. domestica*) and yellow mealworm (*T. molitor*) and evaluated their bioavailability and fermentation of indigestible fractions using a simulated dog digestive model. They found that *H. illucens* and *T. molitor* contain more valine compared to *M. domestica*. This study also showed that the fermentation of *T. molitor* residues showed the best results compared to other insects. Therefore, dog food added with *T. molitor* could be a nutritious alternative for dog meals.[85]

China is one of the countries with a high number of reported edible insect species. This country is leading edible insect patenting, especially on feed applications (Table 3). *T. molitor* and *H. illucens* are common insects used in feed applications. Also, insects such as *M. domestica* and cockroaches are used in the feed industry. In general, insect flours are used in combination with other ingredients including gums, flours from other sources, maltodextrin, etc. Some inventors have used up to 10% of insect powders in the developed products. Images of commonly consumed and utilized insects are presented in Table 5. Members of the Orthoptera order (*A. domestica, L. migratoria* and *S. purpurascens*), Coleoptera order (*Z. morio* and *T. molitor*), Diptera order (*A. ludens* and *H. illucens*), Lepidoptera order (*B. mori*) and Blattodea order (*B. dubia*) are widely used worldwide in food and feed applications as well as consumed directly dried or fried.

Biological potential of insect protein

The biological potential of edible insect proteins has been scarcely studied. However, some authors have reported on the biological potential of insect-derived protein hydrolysates (Table 6). Silkworm pupae (*B. mori*) peptides showed the potential to block the angiotensin-I converting enzyme (ACE) using molecular docking tools. Peptide sequence ASL (Alanine-Serine-Leucine) showed an IC_{50} of 102.15 μM for ACE inhibition. Peptide sequence GNPWM (Glycine-Asparagine-Proline-Tryptophan-Methionine) presented an IC_{50} of 21.70 μM for ACE inhibition.[49,84]

Lee et al. (2011) reported the antidiabetic potential of edible insect protein hydrolysates. They evaluated the inhibition of α-glucosidase enzyme using biochemical assays.[33] This enzyme plays an important role in complex carbohydrates degradation to monosaccharides. *B. mori* protein was hydrolyzed to obtain short-length peptides. Two of the peptides, GQY (Glycine-Glutamine-Tyrosine) and GYG (Glycine-Tyrosine-Glycine) showed good inhibition potential for α-glucosidase with an IC_{50} of 2.7 mg/mL and 1.5 mg/mL, respectively. Additionally, the anti-obesity potential of insect-based ingredients was evaluated using *in vitro* and *in vivo* models. *T. molitor* ethanol extract reduced the expression of lipogenesis-specific genes such as Sterol Regulatory Element-Binding Transcription Factor-1 (SREBP-1), lipoprotein lipase (LPL), stearoyl-CoA desaturase (SCD1) and fatty-acid synthetase (FAS).[4]

Several studies have performed antioxidant biochemical assays on flour, protein hydrolysates and peptides from different edible insects. For instance, *A. domesticus* flour presented antioxidant capacity in (ferric reducing antioxidant power), FRAP and oxygen radical absorbance capacity (ORAC) assays. Thermally treated flour and untreated flour obtained similar results. Concluding that using *A. domesticus* flour for bakery applications could present health benefits against free radicals.[69] *B. mori* proteins and peptides antioxidant potential have been evaluated. Silkworm protein, sericin, presented inhibition for ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) and DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals. This could be due to the high hydrophilic amino acid content of this protein (up to 76%) that could have acted as electron donors. Furthermore, the protein hydrolysates and peptides from the complete *B. mori* proteins showed antioxidant potential in ORAC and DPPH assays. Liu, et al. (2017) studied the purified hydrolysates of *B. mori*, obtaining low molecular weight proteins. In most of their samples, it ranged from 3 to 30 kDa. Samples treated with gastrointestinal digestion obtained consistent protein fractions, while samples treated with proteases were hydrolyzed to peptides and amino acids.[4,33] Protein fractions and peptides obtained from *B. mori* were rich in glutamine, which has been linked to an antioxidant effect due to the carboxyl side, which can interact with metal ions.[83]

Other edible insect species have shown antioxidant potential. For example, housefly (*Musca domestica)* larvae hydrolysate and lesser banded hornet (*Vespa affinis*) aqueous extracts presented antioxidant potential against DPPH radical.[50,90] Peptides obtained from gastrointestinal digestion from dubia roach (*B. dubia*), Madagascar hissing cockroach (*Gromphadorhina portentosa*), migratory locust (*L. migratoria*), king worm (*Zophobas morio*) and cricket (*Amphiacusta annulipes*) presented higher copper chelating activity, DPPH and ABTS radicals inhibition, compared to non-digested proteins.[91]

In most cases, protein extraction with specific proteases, such as α-amilase, pepsin, pancreatin and commercial enzymes (i.e. Flavourzyme, Alcalase, Neutrase) has shown a wide hydrolysis of the protein and short length peptides, from 3 to 50 kDa. These low molecular weight molecules can interact easily, due to the exposed amino acidic sites, with free radical and metal ions, giving this way their antioxidant activity.[34,83,91]

Concluding remarks

Edible insects could be consumed directly or processed as ingredients in food and feed products. Edible insects represent a good source of proteins with good amino acid composition. Nowadays, entomophagy has gained popularity; however, cultural issues limit their consumption. Edible insect protein could be used as an alternative food ingredient. Nevertheless, actual protein extraction methods limit its exploitation due to low extraction yields. Insect protein techno-functional properties provide important information needed during new food product development. The addition of insect ingredients into food matrices must consider insect protein techno-functional properties, the percentage of substitution of regular ingredients and sensory attributes of final products. The correct application of insect-based ingredients in food matrices is key to achieve higher acceptance of final products. Further studies are needed for each insect species, including protein profile, protein structure, protein amino acid sequences and techno-functional properties. The biological potential of edible insect protein and peptides has been reported, including antidiabetic, antihypertensive, anti-obesity and antioxidant potential. Current scientific studies are preliminary and explorative, and more in-depth research is needed to support their biological potential and to elucidate their potential mechanism of action. Insect farming should be considered as the most viable option for edible insect production since collecting implies chemical and microbiological risks. Edible insect research must continue, focusing on high-scale farm production, analytical characterization, techno-functional properties and biological potential. This could generate a better understanding of edible insects and expand their potential applications in the food and feed industry.

Acknowledgments

Author Victor Villaseñor was supported by a scholarship from the Consejo Nacional de Ciencia y Tecnología (CONACyT) México, number 882,350.

Disclosure statement

The authors have no financial or other type of relationship with insect industries that would present a conflict of interest.

ORCID

Luis Mojica http://orcid.org/0000-0001-6994-8711

References

[1] Alfaro-Diaz, A.; Urías-Silvas, J. E.; Loarca-Piña, G.; Gaytan-Martínez, M.; Prado-Ramirez, R.; Mojica, L.; Techno-functional Properties of Thermally Treated Black Bean Protein Concentrate Generated through Ultrafiltration Process. *Lwt*. September 2021, *136*, 2020. DOI: 10.1016/j.lwt.2020.110296.

[2] Ramos-Elorduy, J.; Pino Moreno, J. M.; Escamilla Padro, E.; Alvarado Perez, M.; Lagunez Otero, J.; De Guevara, O, L. Nutritional Value of Edible Insects from the State of Oaxaca, Mexico. *J. Food Compost. Anal.* 1997, *10*(2), 142–157. DOI: 10.1006/jfca.1997.0530.

[3] Ramos-Elorduy Blásquez, J.; Pino Moreno, J. M.; Martínez Camacho, V. M.; Could Grasshoppers Be a Nutritive Meal ? *Food Nutr. Sci.* February, 2012, *(2012*, 164–175. DOI: 10.4236/fns.2012.32025.
[4] Rumpold, B. A.; Schlüter, O. K. Nutritional Composition and Safety Aspects of Edible Insects. *Mol. Nutr. Food Res.* 2013, *57*(5), 802–823. DOI: 10.1002/mnfr.201200735.
[5] Cerritos Flores, R.; Ponce-Reyes, R.; Rojas-García, F. Exploiting a Pest Insect Species *Sphenarium Purpurascens* for Human Consumption: Ecological, Social, and Economic Repercussions. *J. Insect. Food Feed.* 2015, *1*(1), 75–84. DOI: 10.3920/JIFF2014.0013.
[6] Van Huis, A.; Oonincx, D. G. A. B. The Environmental Sustainability of Insects as Food and Feed. A Review. *Agronom. Sust. Develop.* 2017, *37*(5), 5. DOI: 10.1007/s13593-017-0452-8.
[7] Dobermann, D.; Swift, J. A.; Field, L. M.; Opportunities and Hurdles of Edible Insects for Food and Feed. *Nutr. Bull.*2017, *42*, 293–308. DOI:10.1111/nbu.12291.
[8] Ramos-Elorduy, J.; Viejo Montesinos, J. L. Los Insectos Como Alimento Humano: Breve Ensayo Sobre La Entomofagia, Con Especial Referencia a México Insects as Human Food: Short Essay on Entomophagy, with Special Reference to Mexico. *Bol. R. Soc. Esp. Hist. Nay. Sec. Biol.* 2007, *102*(1–4), 61–84.
[9] Evans, J.; Alemu, M. H.; Flore, R.; Frøst, M. B.; Halloran, A.; Jensen, A. B. 'Entomophagy ': An Evolving Terminology in Need of Review. *J. Insect. Food Feed.* 2015, *1*(4), 293–305. DOI: 10.3920/JIFF2015.0074.
[10] Roos, N.; Van Huis, A. Consuming Insects: Are There Health Benefits? *J. Insect. Food Feed.* 2017, *3*(4), 225–229. DOI: 10.3920/JIFF2017.x007.
[11] FAO. Edible Insects. Future Prospects for Food and Feed Security. *Food Agric. Organizat. U N* 2013, *171*. DOI: 10.1017/CBO9781107415324.004.
[12] Ramos-Elorduy, J.;. Anthropo-entomophagy: Cultures, Evolution and Sustainability. *Entomol. Res.* 2009, *39*(5), 271–288. DOI: 10.1111/j.1748-5967.2009.00238.x.
[13] Ramos-Elorduy, J.; Pino Moreno, J. M.; De León, J, M. Análisis químico proximal, vitaminas y nutrimentos inorgánicos de insectos consumidos en el estado de Hidalgo, México. *Folia Entomol. Mex.* 2002, *41*(1), 15–29.
[14] Del Valle, F. R.; Mena, M. H.; Bourges, H. An Investigation into Insect Protein. *J. Food Process. Preserv.* 1982, *6* (2), 99–110. DOI: 10.1111/j.1745-4549.1982.tb00645.x.
[15] Feng, Y.; Chen, X.; Zhao, M.; He, Z.; Sun, L.; Wang, C. Edible Insects in China. *Utilizat. Prospect.* 2018, 184–198. DOI: 10.1111/1744-7917.12449.
[16] Sipponen, M. H.; Mäkinen, O. E.; Rommi, K.; Heiniö, R. L.; Holopainen-Mantila, U.; Hokkanen, S.; ... Nordlund, E. Biochemical and Sensory Characteristics of the Cricket and Mealworm Fractions from Supercritical Carbon Dioxide Extraction and Air Classification. *Eur. Food Res. Technol.* 2018, *244*(1), 19–29. DOI: 10.1007/s00217-017-2931-1.
[17] House, J.;; Consumer Acceptance of Insect-based Foods in the Netherlands: Academic and Commercial Implications. *Appetite.* 2016, September 2015, *107*, 47–58. DOI: 10.1016/j.appet.2016.07.023.
[18] Castro, M.; Chambers, E. Willingness to Eat an Insect Based Product and Impact on Brand Equity: A Global Perspective. *J. Sens. Stud.* 2019, *34*(2), 1–10. DOI: 10.1111/joss.12486.
[19] De-magistris, T.; Pascucci, S.; Mitsopoulos, D. Paying to See a Bug on My Food: How Regulations and Information Can Hamper Radical Innovations in the European Union. *Br. Food J.* 2015, *117*(6), 1777–1792. DOI: 10.1108/BFJ-06-2014-0222.
[20] Igwe, C.; Ujowundu, C.; Nwaogu, L. Chemical Analysis of an Edible African Termite, *Macrotermes Nigeriensis*; a Potential Antidote to Food Security Problem. *Biochem. Analytic. Biochem.* 2012, *01*(1). DOI: 10.4172/2161-1009.1000105.
[21] Ruby, M. B.; Rozin, P.; Chan, C. Determinants of Willingness to Eat Insects in the USA and India. *J. Insect. Food Feed.* 2015, *1*(3), 215–225. DOI: 10.3920/JIFF2015.0029.
[22] Siriamornpun, S.; Thammapat, P. Insects as a Delicacy and a Nutritious Food in Thailand. In *Using Food Science and Technology to Improve Nutrition and Promote National Development*; Robertson, G.L., Lupien, J.R., Eds.; International Union of Food Science & Technology: Mahasarakham, Thailand, 2008; pp 1–11.
[23] Tan, H. S. G.; Verbaan, Y. T.; Stieger, M. How Will Better Products Improve the Sensory-liking and Willingness to Buy Insect-based Foods? *Food Res. Int.* 2017, *92*, 95–105. DOI: 10.1016/j.foodres.2016.12.021.
[24] Cilia, M.; Fish, T.; Yang, X.; Mclaughlin, M.; Thannhauser, T. W.; Gray, S. A Comparison of Protein Extraction Methods Suitable for Gel-based Proteomic. *J. Biomol. Techniq.* 2009, *20*, 201–215.
[25] Hall, F. G.; Jones, O. G.; O'Haire, M. E.; Liceaga, A. M. Functional Properties of Tropical Banded Cricket (*Gryllodes Sigillatus*) Protein Hydrolysates. *Food Chem.* 2017, *224*, 414–422. DOI: 10.1016/j.foodchem.2016.11.138.
[26] Takeda, S.;. *Bombyx Mori. Encyclopedia of Insects (Second Edi)*; Elsevier Inc: Uited Kingdom, 2009. DOi: 10.1016/B978-0-12-374144-8.00040-0.
[27] Caparros Megido, R.; Sablon, L.; Geuens, M.; Brostaux, Y.; Alabi, T.; Blecker, C.; Drugmand, D.; Haubruge, É.; Francis, F. Edible Insects Acceptance by Belgian Consumers: Promising Attitude for Entomophagy Development. *J. Sens. Stud.* 2014, *29*(1), 14–20. DOI: 10.1111/joss.12077.

[28] David-Birman, T.; Raften, G.; Lesmes, U. Effects of Thermal Treatments on the Colloidal Properties, Antioxidant Capacity and *In-vitro* Proteolytic Degradation of Cricket Flour. *Food Hydrocolloids*. 2018, *79*, 48–54. DOI: 10.1016/j.foodhyd.2017.11.044.

[29] Roncolini, A.; Milanović, V.; Cardinali, F.; Osimani, A.; Garofalo, C.; Sabbatini, R.; . . . Aquilanti, L. Protein Fortification with Mealworm (*Tenebrio Molitor* L.) Powder: Effect on Textural, Microbiological, Nutritional and Sensory Features of Bread. *PLoS ONE*. 2019, *14*(2), 1–29. DOI: 10.1371/journal.pone.0211747.

[30] Caparros Megido, R.; Gierts, C.; Blecker, C.; Brostaux, Y.; Haubruge, É.; Alabi, T.; Francis, F. Consumer Acceptance of Insect-based Alternative Meat Products in Western Countries. *Food Qual. Preference*. 2016, *52*, 237–243. DOI: 10.1016/j.foodqual.2016.05.004.

[31] Schouteten, J. J.; De Steur, H.; De Pelsmaeker, S.; Lagast, S.; Juvinal, J. G.; De Bourdeaudhuij, I.; . . . Gellynck, X. Emotional and Sensory Profiling of Insect-, Plant- and Meat-based Burgers under Blind, Expected and Informed Conditions. *Food Qual. Preference*. 2016, *52*, 27–31. DOI: 10.1016/j.foodqual.2016.03.011.

[32] Bußler, S.; Rumpold, B. A.; Jander, E.; Rawel, H. M.; Schlüter, O. K. Recovery and Techno-functionality of Flours and Proteins from Two Edible Insect Species: Meal Worm (*Tenebrio Molitor*) and Black Soldier Fly (*Hermetia Illucens*) Larvae. *Heliyon*. 2016, *2*(12), e00218. DOI: 10.1016/j.heliyon.2016.e00218.

[33] Lee, H. J.; Lee, H. S.; Choi, J. W.; Ra, K. S.; Kim, J. M.; Suh, H. J. Novel Tripeptides with α-glucosidase Inhibitory Activity Isolated from Silk Cocoon Hydrolysate. *J. Agric. Food Chem.* 2011, *59*(21), 11522–11525. DOI: 10.1021/jf202686m.

[34] Sangwong, G.; Sumida, M.; Sutthikhum, V. Antioxidant Activity of Chemically and Enzymatically Modified Sericin Extracted from Cocoons of *Bombyx Mori*.. *Biocatal. Agric. Biotechnol.* 2016, *5*, 155–161. DOI: 10.1016/j.bcab.2016.01.010.

[35] Choi, B. D.; Wong, N. A. K.; Auh, J.-H. Defatting and Sonication Enhances Protein Extraction from Edible Insects. *Korean J. Food Sci. An*. 2017, *37*(6), 955–961. DOI: 10.5851/kosfa.2017.37.6.955.

[36] Haber, M.; Mishyna, M.; Itzhak Martinez, J. J.; Benjamin, O.; (2019) Edible Larvae and Pupae of Honey Bee (*Apis Mellifera*): Odor and Nutritional Characterization as a Function of Diet. *Food Chem.* September 2019, *292*, 197–203. DOI: 10.1016/j.foodchem.2019.04.041.

[37] Zhao, X.; Vázquez-Gutiérrez, J. L.; Johansson, D. P.; Landberg, R.; Langton, M. Yellow Mealworm Protein for Food Purposes - Extraction and Functional Properties. *PLoS ONE*. 2016, *11*(2), 1–17. DOI: 10.1371/journal.pone.0147791.

[38] Zielińska, E.; Karaś, M.; Baraniak, B.; Comparison of Functional Properties of Edible Insects and Protein Preparations Thereof. *LWT Food Sci. Technol.* 2018, October 2017, *91*, 168–174. DOI: 10.1016/j.lwt.2018.01.058.

[39] Yi, L.; Lakemond, C. M. M.; Sagis, L. M. C.; Eisner-Schadler, V.; Van, H. A.; Boekel, M. A. J. S. V. Extraction and Characterisation of Protein Fractions from Five Insect Species. *Food Chem.* 2013, *141*(4), 3341–3348. DOI: 10.1016/j.foodchem.2013.05.115.

[40] Purschke, B.; Tanzmeister, H.; Meinlschmidt, P.; Baumgartner, S.; Lauter, K.; Jäger, H.; Recovery of Soluble Proteins from Migratory Locust (*Locusta Migratoria*) and Characterisation of Their Compositional and Techno-functional Properties. *Food Res. Int.* 2018, December 2017, *106*, 271–279. DOI: 10.1016/j.foodres.2017.12.067.

[41] Purschke, B.; Mendez Sanchez, Y. D.; Jäger, H.; Centrifugal Fractionation of Mealworm Larvae (*Tenebrio Molitor*, L.) For Protein Recovery and Concentration. *LWT Food Sci. Technol.* 2018, October 2017, *89*, 224–228. DOI: 10.1016/j.lwt.2017.10.057.

[42] Purschke, B.; Meinlschmidt, P.; Horn, C.; Rieder, O.; Jäger, H. Improvement of Techno-functional Properties of Edible Insect Protein from Migratory Locust by Enzymatic Hydrolysis. *Eur. Food Res. Technol.* 2017, *244*(6), 999–1013. DOI: 10.1007/s00217-017-3017-9.

[43] De Oliveira, L. M.; Da Silva Lucas, A. J.; Cadaval, C. L.; Mellado, M. S.; Bread Enriched with Flour from Cinereous Cockroach (*Nauphoeta Cinerea*). *Innovative Food Sci. Emerging Technol.* May 2017, *44*, 30–35. DOI: 10.1016/j.ifset.2017.08.015.

[44] Mariod, A. A.; Fadul, H. Extraction and Characterization of Gelatin from Two Edible Sudanese Insects and Its Applications in Ice Cream Making. *Food Sci. Technol. Int.* 2015, *21*(5), 380–391. DOI: 10.1177/1082013214541137.

[45] Gould, J.; Wolf, B. Interfacial and Emulsifying Properties of Mealworm Protein at the Oil/water Interface. *Food Hydrocolloids*. 2018, *77*, 57–65. DOI: 10.1016/j.foodhyd.2017.09.018.

[46] Mintah, B. K.; He, R.; Agyekum, A. A.; Dabbour, M.; Golly, M. K.; Ma, H.; (2020) Edible Insect Protein for Food Applications: Extraction, Composition, and Functional Properties. *J. Food Process Eng.* February 2019, 1–12. 10.1111/jfpe.13362.

[47] Omotoso, O. T.;. An Evaluation of the Nutrients and Some Anti-nutrients in Silkworm, *Bombyx Mori* L. (Bombycidae: Lepidoptera). *Jordan J. Biol. Sci.* 2007, *89*(1), 129–151. DOI: 10.1002/zoo.10031.

[48] Park, Y.-S.; Choi, Y.-S.; Hwang, K.-E.; Kim, T.-K.; Lee, C.-W.; Shin, D.-M.; Gu Han, S. Physicochemical Properties of Meat Batter Added with Edible Silkworm Pupae (*Bombyx Mori*) and Trans- Glutaminase. *Korean J. Food Sci. An*. 2017, *37*(3), 351–359. DOI: 10.5851/kosfa.2017.37.3.351.

[49] Wu, Q.; Jia, J.; Yan, H.; Du, J.; Gui, Z. A Novel angiotensin-I Converting Enzyme (ACE) Inhibitory Peptide from Gastrointestinal Protease Hydrolysate of Silkworm Pupa (*Bombyx Mori*) Protein: Biochemical Characterization and Molecular Docking Study. *Peptides.* 2015, *68*, 17–24. DOI: 10.1016/j.peptides.2014.07.026.

[50] Zepeda-Cisneros, C. S.; Hernández, J. S. M.; García-Martínez, V.; Ibañez-Palacios, J.; Zacharopoulou, A.; Franz, G. Development, Genetic and Cytogenetic Analyses of Genetic Sexing Strains of the Mexican Fruit Fly, *Anastrepha Ludens* Loew (Diptera: Tephritidae). *BMC Genet.* 2014, *15*(Suppl2), S1. DOI: 10.1186/1471-2156-15-S2-S1.

[51] Vercruysse, L.; Smagghe, G.; Herregods, G.; Van Camp, J. ACE Inhibitory Activity in Enzymatic Hydrolysates of Insect Protein. *J. Agric. Food Chem.* 2005, *53*(13), 5207–5211. DOI: 10.1021/jf050337q.

[52] Barać, M. B.; Pešić, M. B.; Stanojević, S. P.; Kostić, A. Z.; Čabrilo, S. B. Techno-functional Properties of Pea (*Pisum Sativum*) Protein Isolates-a Review. *Acta Periodic. Technol.* 2015, *46*(January), 1–18. DOI: 10.2298/APT1546001B.

[53] Ulloa, J. A.; Villalobos Barbosa, M. C.; Resendiz Vazquez, J. A.; Rosas Ulloa, P.; Ramírez Ramírez, J. C.; Silva Carrillo, Y.; González Torres, L. Production, Physico-chemical And Functional Characterization Of A Protein Isolate From Jackfruit (*Artocarpus heterophyllus*) seeds. *CyTA - J. Food.* 2017, *15*(4), 497–507. DOI: 10.1080/19476337.2017.1301554.

[54] Verhoeckx, K. C. M.; Van Broekhoven, S.; Den Hartog-jager, C. F.; Gaspari, M.; De Jong, G. A. H.; Wichers, H. J.; Knulst, A. C. House Dust Mite (Der P 10) and Crustacean Allergic Patients May React to Food Containing Yellow Mealworm Proteins. *Food Chem. Toxicol.* 2014, *65*, 364–373. DOI: 10.1016/j.fct.2013.12.049.

[55] Caparros Megido, R.; Poelaert, C.; Ernens, M.; Liotta, M.; Blecker, C.; Danthine, S.; . . . Francis, F.; (2018) Effect of Household Cooking Techniques on the Microbiological Load and the Nutritional Quality of Mealworms (*Tenebrio Molitor* L. 1758). *Food Res. Int.* August 2017, *106*, 503–508. DOI: 10.1016/j.foodres.2018.01.002.

[56] Ramos-Elorduy, J.;. 1998. *Creepy Crawly Cuisine: The Gourmet Guide to Edible Insects*; 1st. ed.. Park Street Press: Vermont, Uited States.

[57] Iaconisi, V.; Marono, S.; Parisi, G.; Gasco, L.; Genovese, L.; Maricchiolo, G.; . . . Piccolo, G.; Dietary Inclusion of *Tenebrio Molitor* Larvae Meal: Effects on Growth Performance and Final Quality Treats of Blackspot Sea Bream (*Pagellus Bogaraveo*). *Aquaculture*. January 2017, *476*, 49–58. DOI: 10.1016/j.aquaculture.2017.04.007.

[58] Dzerefos, C. M.; Witkowski, E. T. F.; Toms, R. Comparative Ethnoentomology of Edible Stinkbugs in Southern Africa and Sustainable Management Considerations. *J. Ethnobiol. Ethnomed.* 2013, *9*(1), 1. DOI: 10.1186/1746-4269-9-20.

[59] Evans, J.; Müller, A.; Jensen, A. B.; Dahle, B.; Flore, R.; Eilenberg, J.; Frøst, M. B. A Descriptive Sensory Analysis of Honeybee Drone Brood from Denmark and Norway. *J. Insect. Food Feed.* 2016, *2*(4), 277–283. DOI: 10.3920/JIFF2016.0014.

[60] Baiano, A.;. Edible Insects: An Overview on Nutritional Characteristics, Safety, Farming, Production Technologies, Regulatory Framework, and Socio-economic and Ethical Implications. *Trends Food Sci. Technol.* 2020, *100*, 35–50. DOI: 10.1016/j.tifs.2020.03.040.

[61] Ibarra-Herrera, C. C.; Acosta-Estrada, B.; Chuck-Hernández, C.; Serrano-Sandoval, S. N.; Guardado-Félix, D.; Pérez-Carrillo, E. Nutritional Content of Edible Grasshopper (*Sphenarium Purpurascens*) Fed on Alfalfa (*Medicago Sativa*) and Maize (*Zea Mays*). *CyTA - J. Food.* 2020, *18*(1), 257–263. DOI: 10.1080/19476337.2020.1746833.

[62] Sealey, W. M.; Gaylord, T. G.; Barrows, F. T.; Tomberlin, J. K.; McGuire, M. A.; Ross, C.; St-Hilaire, S. Sensory Analysis of Rainbow Trout, *Oncorhynchus Mykiss*, Fed Enriched Black Soldier Fly Prepupae. *Hermetia Illucens. J. World Aquacult. Soc.* 2011, *42*(1), 34–45. DOI: 10.1111/j.1749-7345.2010.00441.x.

[63] Van Huis, A.;. Potential of Insects as Food and Feed in Assuring Food Security. *Annu. Rev. Entomol.* 2013, *58*(1), 563–583. DOI: 10.1146/annurev-ento-120811-153704.

[64] Mutungi, C.; Irungu, F. G.; Nduko, J.; Mutua, F.; Affognon, H.; Nakimbugwe, D.; . . . Fiaboe, K. K. M. Postharvest Processes of Edible Insects in Africa: A Review of Processing Methods, and the Implications for Nutrition, Safety and New Products Development. *Crit. Rev. Food Sci. Nutr.* 2019, *59*(2), 276–298. DOI: 10.1080/10408398.2017.1365330.

[65] Azzollini, D.; Derossi, A.; Fogliano, V.; Lakemond, C. M. M.; Severini, C.; (2018) Effects of Formulation and Process Conditions on Microstructure, Texture and Digestibility of Extruded Insect-riched Snacks. *Innovative Food Sci. Emerging Technol.* September 2017, *45*, 344–353. DOI: 10.1016/j.ifset.2017.11.017.

[66] Cho, J. H.; Zhao, H. L.; Kim, J. S.; Kim, S. H.; Chung, C. H.; (2018) Characteristics of Fermented Seasoning Sauces Using *Tenebrio Molitor* Larvae. *Innovative Food Sci. Emerging Technol.* May 2017, *45*, 186–195. DOI: 10.1016/j.ifset.2017.10.010.

[67] Kim, H. W.; Setyabrata, D.; Lee, Y. J.; Jones, O. G.; Kim, Y. H. B. Effect of House Cricket (*Acheta Domesticus*) Flour Addition on Physicochemical and Textural Properties of Meat Emulsion under Various Formulations. *J. Food Sci.* 2017, *82*(12), 2787–2793. DOI: 10.1111/1750-3841.13960.

[68] Choi, Y.-S.; Kim, T.-K.; Choi, H.-D.; Park, J.-D.; Sung, J.-M.; Jeon, K.-H.; . . . Kim, Y.-B. Optimization of Replacing Pork Meat with Yellow Worm (*Tenebrio Molitor* L.) For Frankfurters. *Korean J. Food Sci. Animal Resour.* 2017, *37*(5), 617–625. DOI: 10.5851/kosfa.2017.37.5.617.

[69] Cuj-Laines, R.; Hernan-Lara, E.; Torruco-Uco, J. G.; Rodriguez-Miranda, J. Efecto de la mezcla de harinas de chapulín y maíz sobre las propiedades funcionales de botanas extruidas. In *Avances de Investigación para el Sector Tecnológico, Ambiental y Alimentario*, FACUNDO JOAQUÍN MÁRQUEZ ROCHA; Instituto Politécnico Nacional (MEXICO), 2017; pp 169–181.
[70] Ayieko, M.; Oriaro, V.; Nyambuga, I. Processed Products of Termites and Lake Flies: Improving Enthomophagy for Food Security within the Lake Victoria Region. *Afr. J. Food Agric. Nutr. Dev.* 2010, *10*(2), 2085–2098. DOI: 10.4314/ajfand.v10i2.53352.
[71] González, C. M.; Garzón, R.; Rosell, C. M.; Insects as Ingredients for Bakery Goods. A Comparison Study of *H. Illucens, A. Domestica* and *T. Molitor* Flours. *Innovative Food Sci. Emerging Technol.* 2018, March, *0–1*. DOI: 10.1016/j.ifset.2018.03.021.
[72] Chico, S.; Alvizo, C.; Martínez, G.; Bravo, T. Elaboración de una botana tipo fritura adicionada con haba y chapulín. *Investigación y Desarrollo En Ciencia y Tecnología de Alimentos*. 2016, *1*(2), 618–622. Retrieved from http://www.fcb.uanl.mx/IDCyTA/files/volume1/2/8/108.pdf
[73] Newton, G. L.; Booram, C. V.; Barker, R. W.; Hale, O. M. Dried *Hermetia Illucens* Larvae Meal as a Supplement for Swine. *J. Anim. Sci.* 1977, *44*(3), 395–400. DOI: 10.2527/jas1977.443395x.
[74] Bondari, K.; Sheppard, D. C. Soldier Fly, *Hermetia Illucens* L., Larvae as Feed for Channel Catfish, *Ictalurus Punctatus* (Rafinesque), and Blue Tilapia, *Oreochromis Aureus* (Steindachner). *Aquacult. Res.* 1987, *18*(3), 209–220. DOI: 10.1111/j.1365-2109.1987.tb00141.x.
[75] Magalhães, R.; Sánchez-López, A.; Leal, R. S.; Martínez-Llorens, S.; Oliva-Teles, A.; Peres, H. Black Soldier Fly (*Hermetia Illucens*) Pre-pupae Meal as a Fish Meal Replacement in Diets for European Seabass (*Dicentrarchus Labrax*). *Aquaculture*. 2017, *476*(April), 79–85. DOI: 10.1016/j.aquaculture.2017.04.021.
[76] Gasco, L.; Henry, M.; Piccolo, G.; Marono, S.; Gai, F.; Renna, M.; . . . Chatzifotis, S. *Tenebrio Molitor* Meal in Diets for European Sea Bass (*Dicentrarchus Labrax* L.) Juveniles: Growth Performance, Whole Body Composition and in Vivo Apparent Digestibility. *Anim. Feed Sci. Technol.* 2016, *220*, 34–45. DOI: 10.1016/j.anifeedsci.2016.07.003.
[77] Biasato, I.; De Marco, M.; Rotolo, L.; Renna, M.; Lussiana, C.; Dabbou, S.; . . . Schiavone, A. Effects of Dietary *Tenebrio Molitor* Meal Inclusion in Free-range Chickens. *J. Animal Physiol. Animal Nutr.* 2016, *100*(6), 1104–1112. DOI: 10.1111/jpn.12487.
[78] De Marco, M.; Martínez, S.; Hernandez, F.; Madrid, J.; Gai, F.; Rotolo, L.; . . . Schiavone, A. Nutritional Value of Two Insect Larval Meals (*Tenebrio Molitor* and *Hermetia Illucens*) for Broiler Chickens: Apparent Nutrient Digestibility, Apparent Ileal Amino Acid Digestibility and Apparent Metabolizable Energy. *Anim. Feed Sci. Technol.* 2015, *209*, 211–218. DOI: 10.1016/j.anifeedsci.2015.08.006.
[79] Alegbeleye, W. O.; Obasa, S. O.; Olude, O. O.; Otubu, K.; Jimoh, W. Preliminary Evaluation of the Nutritive Value of the Variegated Grasshopper (*Zonocerus Variegatus* L.) For African Catfish *Clarias Gariepinus* (Burchell. 1822) Fingerlings. *Aquacult. Res.* 2012, *43*(3), 412–420. DOI: 10.1111/j.1365-2109.2011.02844.x.
[80] Belghit, I.; Liland, N. S.; Waagbø, R.; Biancarosa, I.; Pelusio, N.; Li, Y.; Lock, E.-J.; (2018) Potential of Insect-based Diets for Atlantic Salmon (*Salmo Salar*). *Aquaculture*. November 2017, *491*, 72–81. DOI: 10.1016/j.aquaculture.2018.03.016.
[81] Irungu, F. G.; Mutungi, C. M.; Faraj, A. K.; Affognon, H.; Kibet, N.; Tanga, C.; . . . Fiaboe, K. K. M. Physico-chemical Properties of Extruded Aquafeed Pellets Containing Black Soldier Fly (*Hermetia Illucens*) Larvae and Adult Cricket (*Acheta Domesticus*) Meals. *J. Insect. Food Feed.* 2018, *4*(1), 19–30. DOI: 10.3920/JIFF2017.0008.
[82] Tze, F. T.; Hing, W. N. Fish Feed Formulation Using Black Soldier Fly Pre-pupae from Fruit Waste. *J. Eng. Appl. Sci.* 2017. DOI: 10.3923/jeasci.2017.6393.6397.
[83] Liu, Y.; Wan, S.; Liu, J.; Zou, Y.; Liao, S. Antioxidant Activity and Stability Study of Peptides from Enzymatically Hydrolyzed Male Silkmoth. *J. Food Process. Preserv.* 2017, *41*(1), 1. DOI: 10.1111/jfpp.13081.
[84] Tao, M.; Wang, C.; Liao, D.; Liu, H.; Zhao, Z.; Zhao, Z. Purification, Modification and Inhibition Mechanism of Angiotensin I-converting Enzyme Inhibitory Peptide from Silkworm Pupa (*Bombyx Mori*) Protein Hydrolysate. *Process Biochem.* 2017, *54*, 172–179. DOI: 10.1016/j.procbio.2016.12.022.
[85] Bosch, G.; Vervoort, J. J. M.; Hendriks, W. H. In Vitro Digestibility and Fermentability of Selected Insects for Dog Foods. *Anim. Feed Sci. Technol.* 2016, *221*, 174–184. DOI: 10.1016/j.anifeedsci.2016.08.018.
[86] Tanaka, S.; Nishide, Y. A Green Morph of the Migratory Locust, *Locusta Migratoria* L. (Orthoptera: Acrididae) that Occurred after Inbreeding. *J. Orthoptera Res.* 2012, *21*(2), 175–177. DOI: 10.1665/034.021.0205.
[87] Adámková, A.; Kourimská, L.; Borkovcová, M.; Kulma, M.; Mlček, J. Nutritional Values of Edible Coleoptera (*Tenebrio Molitor, Zophobas Morio* and *Alphitobius Diaperinus*) Reared in the Czech Republic. *Potravinarstvo*. 2016, *10*(1), 663–671. DOI: 10.5219/609.
[88] Worek, F.; Seeger, T.; Neumaier, K.; Wille, T.; Thiermann, H. *Blaptica Dubia* as Sentinels for Exposure to Chemical Warfare Agents – A Pilot Study. *Toxicol. Lett.* 2016, *262*, 12–16. DOI: 10.1016/j.toxlet.2016.09.006.
[89] Zhang, H.; Wang, P.; Zhang, A.-J.; Li, X.; Zhang, J.-H.; Qin, Q.-L.; Wu, Y.-J. Antioxidant Activities of Protein Hydrolysates Obtained from the Housefly Larvae. *Acta Biol. Hungarica*. 2016, *67*(3), 236–246. DOI: 10.1556/018.67.2016.3.2.
[90] Dutta, P.; Dey, T.; Manna, P.; Kalita, J. Antioxidant Potential of *Vespa Affinis* L., A Traditional Edible Insect Species of North East India. *PLoS ONE*. 2016, *11*(5), 1–19. DOI: 10.1371/journal.pone.0156107.

[91] Zielińska, E.; Karaś, M.; Jakubczyk, A. Antioxidant Activity of Predigested Protein Obtained from a Range of Farmed Edible Insects. *Int. J. Food Sci. Technol.* 2017, *52*(2), 306–312. DOI: 10.1111/ijfs.13282.
[92] Seo, M.; Goo, T. W.; Chung, M. Y.; Baek, M.; Hwang, J. S.; Kim, M. A.; Yun, E. Y. *Tenebrio Molitor* Larvae Inhibit Adipogenesis through AMPK and MAPKs Signaling in 3T3-L1 Adipocytes and Obesity in High-fat Diet-induced Obese Mice. *Int. J. Mol. Sci.* 2017, *18*(3), 3. DOI: 10.3390/ijms18030518.