Journal of Functional Foods 76 (2021) 104316

Contents lists available at ScienceDirect

Journal of Functional Foods

journal homepage: www.elsevier.com/locate/jff

So different, yet so alike Pancrustacea: Health benefits of insects and shrimps

Maryia Mishyna [a,*], Miodrag Glumac [b]

[a] Wageningen University & Research, Food Quality & Design Group, Wageningen, the Netherlands
[b] Zhejiang Gongshang University, School of Food Science and Biotechnology, Hangzhou, PR China

ARTICLE INFO

Keywords:
Insects
Shrimps
Health benefits
Hydrolysates
Bioactivity
Functional food

ABSTRACT

Insects and shrimps represent the clade Pancrustacea of the phylum Arthropods. Being valuable sources of nutrients and bioactive compounds, insects and shrimps possess several physiological similarities but are processed and consumed in different ways. This review provides a comparative overview of the additional health benefits of insects and shrimps to assess their potential as a functional food. Hydrolysates, their antioxidant and angiotensin-converting enzyme inhibitory activities, fatty acids, cholesterol, minerals, vitamins, carotenoids, phenolic compounds, dietary fiber, as well as, *in vivo* studies on the consumption of insects and shrimps are discussed. Both organisms could be viewed as marine and terrestrial counterparts of high nutritional importance and valuable sources of bioactive compounds and proteins needed for designing new functional food and supplements. However, more *in vivo* and clinical studies are needed along with the safety and allergy assessment of insects to ensure their safety for human consumption.

1. Introduction

Arthropods enclose large animal taxa that include crustaceans, insects, myriapods, and chelicerates, united by common features - the clear segmentation of their bodies, a sclerotized cuticle, and jointed appendages (Fig. 1) (Budd & Telford, 2009). Both insects and shrimps can be also classified as belonging to the clade Pancrustacea. Insects are the largest class of Arthropods, and their consumption was happening throughout the whole history of humankind. Eating cicadas as a delicacy in Ancient Greece, the larvae of longhorn beetle in the city of Rome or locusts and grasshoppers in Ethiopia has been well documented and has reached the present time (van Huis et al., 2013). However, only a few insect species such as silkworm and honey bee were domesticated (Lecocq, 2018). In countries with lower monetary income, insects remained a part of a diet and even considered as a delicacy, for example, palm weevil (Kelemu et al., 2015; van Huis, 2003).

Crustaceans (shrimps, prawns, crabs, lobsters, krill) are consumed and farmed worldwide with more than 300 species of shrimps that are of economic interest (Gillett, 2008). Shrimp farming has begun with natural migration of wild shrimps into tidal impoundments forming incidental crops of shrimps in Asia centuries ago. During the 1970s technologies of industrial shrimp farming started to develop, focusing for instance on shrimp nutrition (Chamberlain, 2012). Once considered as acceptable food, shrimps have long become a delicacy and a highly desired source of proteins.

Inexorable population growth and environmental problems recently increased ecological awareness and initiated the modernization of the agricultural system towards a more sustainable model. As a response to the changing world, the shrimp industry proposes indoor farming that lowers the risk of disease, increases shrimp quality, product traceability, and has a positive effect on the environment (Rubel, Woods, Pérez, Unnikrishnan, Felde, & Zum, 2019). Ecological issues have also caused a growing global interest in alternative protein sources. In this regard, edible insects offer a promising solution both in terms of high nutritional value (van Huis et al., 2013) and the sustainability of their production (van Huis & Oonincx, 2017). Additionally, insects can be reared on food waste or by-products of food manufacturing (Oonincx, van Broekhoven, van Huis, & van Loon, 2015), following the concept of a circular economy and minimizing the loss of nutrients in food production systems.

The idea of “Let food be thy medicine and medicine be thy food” is attributed to Hippocrates (460–377 BC), but was also known in ancient China and then revived in Japan (Arai, 2005). Generally, functional food is defined as “any food that has a positive impact on an individual’s health, physical performance, or state of mind in addition to its

* Corresponding author.
E-mail address: maryia.mishyna@wur.nl (M. Mishyna).

https://doi.org/10.1016/j.jff.2020.104316
Received 24 July 2020; Received in revised form 19 November 2020; Accepted 21 November 2020
Available online 25 December 2020

nutritious value" (Rincón-León, 2003). Nowadays, the design of functional foods aims to promote health by targeting specific physiological processes that lead to disease prevention (Vattem & Maitin, 2016). They may originate from plants, animals, microbes, algae, mushrooms, and other sources targeting cancer, immune system, aging, diabetes, gastrointestinal, and women's health (Doyon & Labrecque, 2008; Vattem & Maitin, 2016). Insects were extensively studied as a source of bioactive compounds for medicine (Costa-Neto, 2005), but little is known about their additional functional potential when consumed as food. On the contrary, shrimps are well studied as a source of nutrients, but the added-value potential of shrimp by-products was the main interest of recent studies. Therefore, this review aims to compare insects and shrimps for their health-promoting effects as food and to assess if they meet the criteria of functional food and food ingredients.

2. Consumption of insects and shrimps

The processing and consumption approaches differ for insects and shrimps and to a great extent are related to their sizes.

Cultivated shrimps have been reported to have sizes ranging from 8 to 23 cm judged by total their length. The exoskeleton and cephalothorax make at least 40% of the total shrimp body (Randriamahatody et al., 2011), while shrimp muscles are used directly for consumption. Shell loosening and enhancement of peelability of shrimps can be enhanced through enzymatic processes, microwave, or ultrasound treatments (Dang et al., 2018). Shrimp by-products such as exoskeleton and head, are used for further extraction of bioactive compounds and chitin.

Insects are generally consumed as whole, but in some cases wings and legs for instance from locusts, are removed in order to lower chitin content and to prevent sticking in the throat if an insect is eaten entirely. On an industrial level, insects are processed into insect powder, protein-enriched and fiber-enriched fractions, and fat. Separation of pure muscle fractions from insects by peeling, that is feasible for shrimps, is hardly possible on the large-scale processing nowadays. Moreover, peeling is more relevant for adult insect species with well developed exoskeleton, for instance locusts, than to soft larvae of yellow mealworm (*Tenebrio molitor*) or pupae of black soldier fly (*Hermetia illucens*). The smaller size of insects also hardens its peeling in comparison to shrimps.

The facts described above highlight the differences in the consumption of insects and shrimps that is reflected in their different biology, anatomy, and morphometrical properties. All these factors are taken into account in further discussion.

3. Nutrients and bioactive compounds of insects and shrimps

Insects and shrimps have high protein content ranging between 7–48 and 13–27 g/100 g fresh weight, respectively. Protein content largely

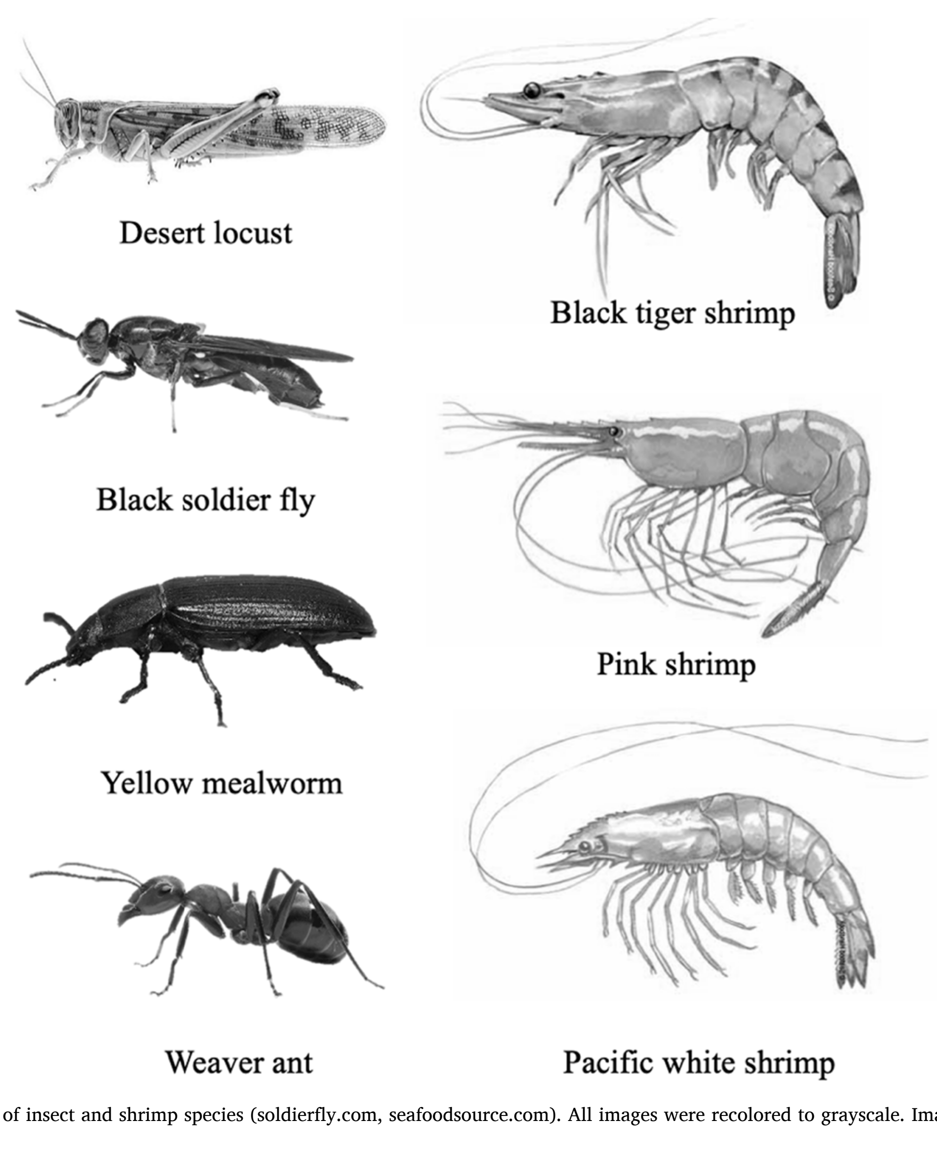

Fig. 1. Images of insect and shrimp species (soldierfly.com, seafoodsource.com). All images were recolored to grayscale. Images not to scale.

varies between species and depends on their development stage (van Huis et al., 2013). For instance, silkworm (*Bombyx mori*) larvae protein isolate, larvae and pupae of a honey bee (*Apis mellifera*), green tiger (*Penaeus semisulcatus*), and speckled shrimps (*Metapenaeus monoceros*) are especially rich in glutamic acid, aspartic acid, leucine, and lysine (Mishyna, Martinez, Chen, & Benjamin, 2019; Wu, Jia, Tan, Xu, & Gui, 2011; Yanar & Çelik, 2006). The abundance of individual amino acids was also reported to be influenced by seasonal variation (Yanar & Çelik, 2006) and a diet type (Mente, Coutteau, Houlihan, Davidson, & Sorgeloos, 2002). In general, the amino acid composition of insects and shrimps meet requirements for the human diet and comparable to animal proteins (Table 1) (Ghosh, Lee, Jung, & Meyer-Rochow, 2017; van Huis et al., 2013; Yanar & Çelik, 2006; Zielińska, Baraniak, Karaś, Rybczyńska, & Jakubczyk, 2015).

Lipid content, its composition, degree of saturation, and presence of cholesterol in insects and shrimps are highly dependent on species, development stage, and origin of the material used for fatty acid analysis (Table 2). Generally, insects have higher fat content ranging from 2 to 62% (Williams, Williams, Kirabo, Chester, & Peterson, 2016), comparing to shrimps that contain around 1% of fat (Dayal et al., 2013). In general, insect fatty acid profile is similar to that of vegetable oils and animal fats (Tzompa-Sosa & Fogliano, 2017) and both insects and shrimps are rich in unsaturated fatty acids. Particularly, adult locusts (*Schistocerca gregaria*) and house crickets (*Acheta domesticus*), as well as deep-water rose shrimps (*Parapenaeus longirostris*), have around 65% of unsaturated fatty acids (Tzompa-Sosa, Yi, van Valenberg, van Boekel, & Lakemond, 2014; Yerlikaya, Topuz, Buyukbenli, & Gokoglu, 2013; Zielińska et al., 2015). Around 75–76% of total fatty acids in whole larvae of yellow mealworms are also unsaturated fatty acids (Tzompa-Sosa et al., 2014), that is similar to the ratio of unsaturated fatty acids in muscles and by-products of adult Northern pink shrimps (*Pandalus borealis*) and spotted shrimps (*Trachypena curvirostris*) (Heu, Kim, & Shahidi, 2003). However, high ratio of saturated fatty acids (51–68%) was typical for black soldier fly (*Hermetia illucens*) larvae grown on feeding media with the inclusion of the brown algae (Liland et al., 2017). Omega-6/omega-3 fatty acids ratio is generally lower for shrimp (0.2–0.8) meat comparing to whole insects (1.2–27) (Table 2), which makes shrimps more desirable for the reduction of the risk of a number of chronic diseases. While insects fat needs additional processing or mixing with other fat sources in order to achieve the desired ratio of omega-6/omega-3. It should be mentioned, that the oil extraction method significantly affects the yield and omega-6/omega-3 ratio (Tzompa-Sosa et al., 2014) and can be controlled by diet (Lehtovaara et al., 2017).

Cholesterol is the major sterol in shrimps and insects and can not be synthesized *de novo* (Behmer & Nes, 2003; Kumar et al., 2018). The level of cholesterol in shrimps (173 mg/100 g) is considered moderate, which is lower than in eggs (400 mg/100 g) but higher than in chicken (100 mg/100 g) and beef (70 mg/100 g) (Dayal et al., 2013). It has been also stated that the level of cholesterol in shrimps is not harmful due to low content of saturated fatty acids (Dayal et al., 2013). Comparable concentration of cholesterol to conventional meat sources was reported for *Tenebrio molitor* (669.4 mg/kg), that was significantly lower than in *Zophobus morio* (1594.9–1784.1 mg/kg) (Sabolová, Adámková, Kouřimská, Chrpová, & Pánek, 2016). However, in 2015, US Departments of Agriculture and Health and Human Services announced the dropping of dietary cholesterol as a “nutrient of concern”, that is supported by scientific evidence on no relationship between dietary cholesterol and serum cholesterol or clinical cardiovascular events (Mozaffarian & Ludwig, 2015).

Minerals are essential constituents of insects and shrimps, and the content of all minerals largely varies between species. A comprehensive analysis by Rumpold and Schlüter (2013) demonstrated that edible insects are generally low in calcium (0.04–2010 mg/100 g based on dry matter), potassium (0.20–3259 mg/100 g based on dry matter), and do not fulfill the requirements for the daily uptake of these minerals for adults. Low potassium content was characteristic for shrimps as well, but shrimps were reported as a good source of calcium (the daily value of foods, <10% and 10–25%, respectively) (Dayal et al., 2013). According to FAO (Food and Agriculture Organization of the United Nations, 2016), the calcium content in shrimps varies between 21 (raw flesh of *Pandalus* shrimps) and 583 mg/100 g fresh weight (raw flesh of eastern school shrimp *Metapenaeus macleaya*).

Crickets and locusts are rich in magnesium (Rumpold & Schlüter, 2013), which is similar to the dominance of magnesium in black tiger (*Penaeus monodon*) and white shrimp (*Penaeus vannamei*) meat (Sriket,

Table 1
Amino acid composition (mg/g protein) of insects, shrimps, and FAO standard for adults.

Amino acid	Mealworm (*Tenebrio molitor*), larvae	Locust (*Schistocerca gregaria*), adult	Tiger prawn (*Penaeus monodon*), adult[a,b]	Southern pink shrimp (*Penaeus notialis*), adult[b]	WHO, 2007
Alanine	44.3	88.8	49.5	50	–
Arginine	25.6	39.8	82.8	69	–
Aspartic acid	50.5	66.1	88.3	90[c]	–
Cysteine	5.5	3.6	6.3[d]	61[d]	6
Glutamic acid	79.7	107.5	139.6	126[e]	–
Glycine	31.8	49.4	49.0	64	–
Histidine	16.1	20.6	19.1	25	15
Isoleucine	21.4	28.2	38.9	36	30
Leucine	45.8	77.7	66.1	70	59
Lysine	26.7	35.1	68.0	71	45
Methionine	9.6	8.2	23.0	58	16
Phenylalanine	16.1	18.7	32.0	27	30
Proline	43.4	67.1	32.9	75	–
Serine	28.8	33.7	30.0	45	–
Threonine	26.1	35.5	32.3	58	23
Tryptophan	na[f]	na	10.7	na	–
Tyrosine	28.8	33.1	32.4	33	–
Valine	39.7	56.6	42.1	42	39
Reference	(Zielińska et al., 2015)	(Zielińska et al., 2015)	(Peñaflorida, 1989)	(Akintola, 2015)	(WHO/FAO/UNU, 2007)

[a] Converted from g AA/100 g protein.
[b] Muscle.
[c] Reported as aspartate.
[d] Reported as cystine.
[e] Reported as glutamate.
[f] na – not analysed.

Table 2
Fat characteristics of insects and shrimps.

Latin name	Common name	Development, fraction	Fat, %	Saturated fatty acids, %	Unsaturated fatty acids, %	n-6 fatty acid, %	n-3 fatty acid, %	n6/n3 ratio	Reference
Insects									
Schistocerca gregaria	Locust	Adult, whole	13.0[a]	35.3	64.6[g]	14.0	11.4	1.2	(Zielińska et al., 2015)
Acheta domesticus	House cricket	Adult, whole	1.6–8.0[b-c]	31.3–34.4[c]	64.2–68.3[c]	29.1–34.4[c]	2.0–2.5[c]	12.8–16.9[c]	(Tzompa-Sosa et al., 2014)
Tenebrio molitor	Yellow mealworm	Larvae, whole	7.8–12.9[b-c]	23.5–24.4[c]	75.0–76.2[c]	21.7–23.4[c]	0.8–0.9[c]	24.4–27.2[c]	(Tzompa-Sosa et al., 2014)
Hermetia illucens	Black soldier fly	Larvae, whole[h]	33.1[a]	67.9	31.6[g]	18.0	1.4	12.9[d]	(Liland et al., 2017)
Oecophylla smaragdina	Red ant	Adults, whole	9.3[a]	31.9	68.1[g]	8.4	1.0	8.4[d]	(Oranut, Subhachai, Shen, & Li, 2010)
Shrimps									
Crangon crangon	Brown shrimp	Adult, beheaded and peeled	1.0	33.0	51.2[g]	6.7	22.3	0.3[d]	(Turan, Kaya, & Erdem, 2011)
Aristeomorpha foliacea	Giant red shrimp	Adult, beheaded and peeled	2.2	31.2	68.8[g]	4.5	29.4	0.2	(Yerlikaya et al., 2013)
Parapenaeus longirostris	Deep-water rose shrimp	Adult, beheaded and peeled	1.8	35.7	64.3[g]	6.9	27.0	0.3	(Yerlikaya et al., 2013)
Metapenaeus monoceros	Speckled shrimp	Adult, beheaded and peeled	2.2	33.3	66.7[g]	19.0	23.8	0.8	(Yerlikaya et al., 2013)
Pandalus borealis	Northern pink shrimp	Adult, muscle	0.4	25.4	74.2[g]	12.2 [d]	31.1[d]	0.4[d]	(Heu et al., 2003)
Pandalus borealis	Northern pink shrimp	Adult, by-products	0.6	25.9	73.5[g]	11.2[d]	24.2[d]	0.5[d]	(Heu et al., 2003)
Trachypena curvirostris	Spotted shrimp	Adult, muscle	0.3	26.2	73.5[g]	12.0[d]	31.3[d]	0.4[d]	(Heu et al., 2003)
Trachypena curvirostris	Spotted shrimp	Adult, by-products	0.7	26.1	73.3[g]	11.4[d]	26.1[d]	0.4[d]	(Heu et al., 2003)
Oratosquilla nepa	Mantis shrimp	Adult, whole	1.3	4.3	93.0[g]	12.0	26.0	0.5	(Chaijan & Panpipat, 2019)

a –based on dry weight, b – based on fresh weight, c – variations are due to differences in the methods of lipid extraction, d – calculated based on the available data, e – nd-not determined, f – cholesterol ester, g – calculated as sum of monounsaturated and polyunsaturated fatty acids, h – the data are for larvae grown on pure plant-based medium.

Benjakul, Visessanguan, & Kijroongrojana, 2007). Cricket powder is rich in copper, manganese and zinc (2.33–4.51, 4.1–12.5, and 12.8–21.8 mg/100 g of dry matter, respectively) (Montowska, Kowalczewski, Rybicka, & Fornal, 2019). Latunde-Dada et al. demonstrated, that cricket (*Gryllus bimaculatus*) and sirloin beef had higher levels of iron, calcium and manganese than a grasshopper (*Sphenarium purpurascens*), mealworm (*Tenebrio molitor*) and buffalo worms (*Alphitobius diaperinus*) and the mentioned insects exhibited a higher amount of chemically available calcium, copper, magnesium, manganese and zinc than beef (Latunde-Dada, Yang, & Vera Aviles, 2016). In contrast, deep-water rose shrimp meat had a low content of iron and zinc (66.20 and 36.74 mg/kg, respectively) (Cankirilig & Berik, 2017). Insects are generally low in sodium with the exception of some caterpillars (Rumpold & Schlüter, 2013). In particular, Finke showed, that sodium content varies between species from 165 mg/kg (waxworms) and 475 mg/kg (superworms) to 1340 mg/kg in adult house crickets (Finke, 2002). In comparison, sodium content in beef, pork and chicken varies between 63 and 77 mg/100 g (Desmond, 2006) and from 112 mg/100 g (raw flesh of speckled shrimp) to 630 mg/100 g (raw flesh of *Pandalus* shrimps) for shrimp species (Food and Agriculture Organization of the United Nations, 2016).

Little is known about vitamins of edible insects, but they are generally rich in B_2 (riboflavin), B_5 (pantothenic acid), and B_7 (biotin) (Rumpold & Schlüter, 2013). Riboflavin of superworms and mealworms larvae, and adult house crickets was determined at the concentrations of 7.5, 8.1, and 34.1 mg/kg, respectively (Finke, 2002). These values are higher than those in shrimps, for example, riboflavin content varies between 0.05 and 0.11 mg/100 g fresh weight for raw flesh of Whiteleg shrimp and Palaemonid shrimps, respectively (Food and Agriculture Organization of the United Nations, 2016). The concentration of B complex vitamins remained constant at all development stages of grasshopper (*Brachystola magna*) and on contrary vitamin C increased from 19.86 in eggs to 34.55 mg/100 g in adults (Zamudio-Flores et al., 2019). Insects generally have low amount of vitamin C (Rumpold & Schlüter, 2013), that is a comparable trait to shrimp species (Food and Agriculture Organization of the United Nations, 2016).

Usually delivered from animal sources, vitamin B_{12} was determined in insects at the concentrations of 1.08 μg/100 g in yellow mealworm, 2.88 μg/100 g in cricket, and 0.84 and 13.2 μg/100 g in grasshopper (*Locusta migratoria*) and cockroach (*Shelfordella lateralis*), respectively (Schmidt, Call, Macheiner, & Mayer, 2019). Similar values of B_{12} were detected in raw shrimp flesh, i.e. 1.3 mcg/100 g (whiteleg shrimp), 2.1 mcg/100 g (eastern school shrimp), 3.5 mcg/100 g (*Pandalus* shrimps), 5 mcg/100 g (common shrimp) (Food and Agriculture Organization of the United Nations, 2016). It has been shown that fat-soluble A, D and E vitamins showed a noticeable increase across the developmental stages (from egg to adult) of grasshopper (*Brachystola magna*) with the maximum in the adult stages and values of 0.39, 5.25, and 145.36 mg/100 g, respectively (Zamudio-Flores et al., 2019). In silkworms, on the contrary, the content of vitamin A is significantly higher than vitamin E, but both vitamins were found to be lower than in carrots, sweet potato, almonds, and spinach (Paul & Dey, 2014).

Phenolic compounds have a wide range of functions in particular in scavenging oxidative stress as they are responsible for the antioxidative properties (Oliveira, Carvalho, & Melo, 2014). Substantial amounts of phenolic compounds and flavonoids (744.5–881.0 and 423.6–552.6 mg/100 g, respectively depending on varieties) were found in steamed and freeze-dried mature silkworm larval powders that suggest their health-improvement effects (Ji et al., 2017). Apigenin was determined as one of the most abundant flavonoid in the unprocessed and processed edible stink bugs (*Encosternum delegorguei*) (37.13 and 34.52 ng/g, respectively), while rutin was found at the lowest concentration (2.89 ng/g)

(Musundire, Osuga, Cheseto, Irungu, & Torto, 2016). Ethanolic extracts from the adult large black chafer beetle (*Holotrichia parallela*) were especially rich in catechins, however the authors concluded that it is not clear whether catechin is originated from insect cuticles or from the plants which insects eat (Liu et al., 2012).

Saponins contain a triterpene or steroid aglycone and one or more sugar chains and dietary saponins are known as potential pancreatic lipase inhibitors, antioxidants, immune regulators, and reported to be promising against the development of obesity (Guclu-Ustundag & Mazza, 2007; Jeepipalli, Du, Sabitaliyevich, & Xu, 2020). Very little is known about saponins from insects and shrimps. The presence of saponins (6.88 and 7.00%, respectively) was shown in larvae and pupae of silkworm along with tannic acid, oxalate, phytate, and phytin phosphorus (Omotoso, 2015). Saponins were also determined (53.3 Diosgenin equivalents per 100 g of the sample) in a cricket (*Henicus whellani*) along with alkaloids (52.3 g/100 g) and tannins (0.17 Gallic acid equivalents per 100 g of the sample) (Kunatsa, Chidewe, & Zvidzai, 2020).

The exoskeleton of many Arthropods, including insects and crustaceans consists of chitin, a long-chain polymer of N-acetylglucosamine. Chitin contains 90.6% of total dietary fiber (Maezaki, Yamazaki, Mizuochi, & Tsuji, 1993) and it can be defined as a functional food component providing special benefits to food, for instance contributing to colonic health, coronary artery health, and cholesterol reduction amongst many others (Prosky, 2000). Chitin content largely depends on an insect species and their development stage and was eastimated as 38.1 mg/kg, 81.5 mg/kg, and 137.2 mg/kg for waxworm larvae, cricket nymphs, and adult mealworms, respectively (Finke, 2007). Chitin can be eliminated from insects during the production of food ingredients through a number of extraction procedures. Unlike insects, shrimps are easier peeled and pure shrimp meat is consumed, that eliminates the consumption of chitin. In its turn, shrimp waste (exoskeleton and heads) is a valuable source of chitin, that can be consequently deacetylated into chitosan. Health-promoting benefits of dietary chitosan were previously discussed in literature (Inanli, Tümerkan, El Abed, Regenstein, & Özogul, 2020; Shahidi, Arachchi, & Jeon, 1999). It should be mentioned, that chitosan can be also produced from chitin of whole insects or chitin-enriched fractions of processed insects.

4. Health-promotion properties of insects and shrimps

Both insects and shrimps contain a diversity of amino acids, fatty acids, and bioactive compounds that exhibit a variety of health-promoting characteristics (Fig. 2). These constituents are investigated in both *in vitro* and *in vivo* experimental setups and provide new insights and clues on how they might influence health in various ways and more importantly how they can provide a function to foods that consist of them. These will be discussed and elaborated upon herewith.

4.1. In vitro studies

4.1.1. Angiotensin converting enzyme inhibitory activity (ACE)

Angiotensin I converting enzyme (ACE) is involved in the regulation of treating hypertension (Iwaniak, Minkiewicz, & Darewicz, 2014) and congestive heart failure. Comparative *in vitro* analysis of peptides obtained from the silkworm, the yellow mealworm, the cotton leafworm (*Spodoptera littoralis*) and the weaver ant (*Oecophylla smaragdina)* by various types of enzymatic hydrolysis showed that they are comparable in ACE inhibitory activity to bioactive peptides obtained from other animal sources (Cito, Botta, Francardi, & Dreassi, 2017). Gastrointestinal digestion of the cotton leafworm, silkworm, locust, and bumble bee (*Bombus terrestris*) led to the increase of ACE inhibitory activity of hydrolysates suggesting insect proteins as antihypertensive component (Vercruysse, Smagghe, Herregods, & Van Camp, 2005; Vercruysse, Smagghe, Matsui, & Van Camp, 2008; Wu et al., 2011). Moreover, hydrolysates components of silkworms from less than 500 to about

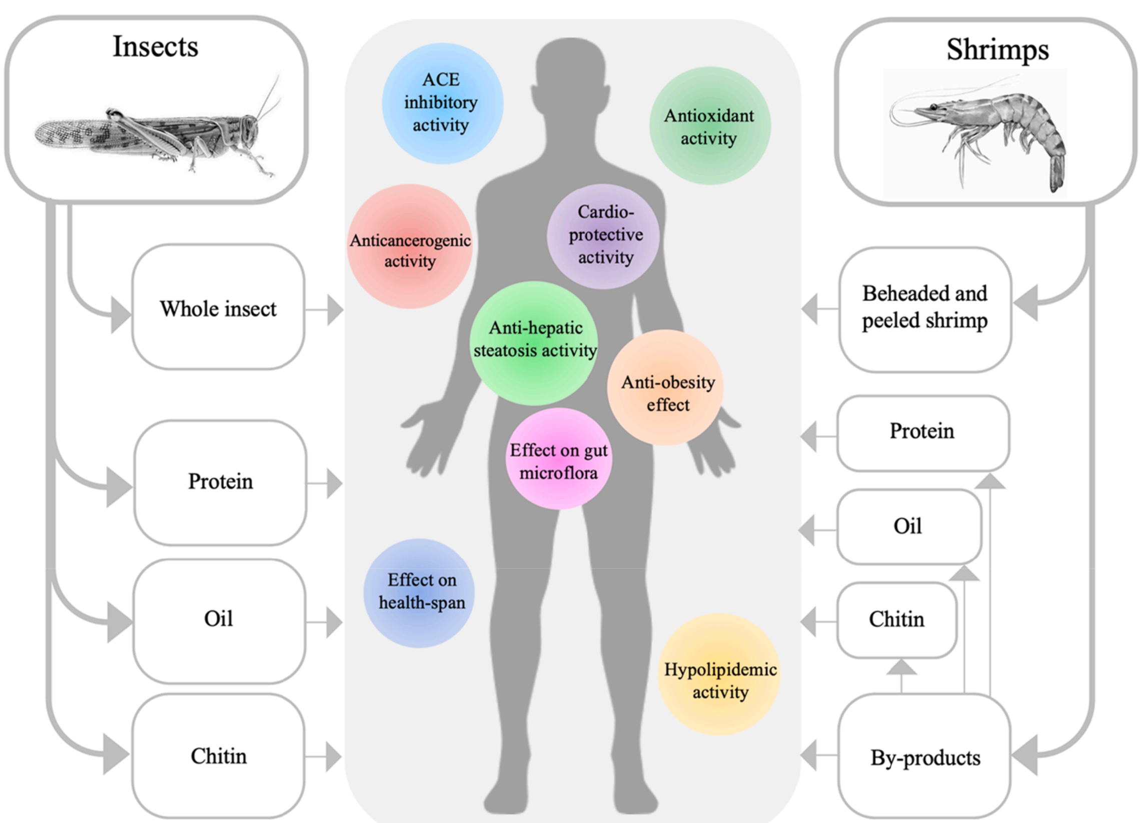

Fig. 2. Ways of insect and shrimp consumptions and their potential health benefits.

1000 Da exhibited inhibitory activity on ACE (Wang et al., 2008), while, the low molecular weight constituents (<6 kDa) were found to mainly contribute to ACE-inhibitory activity ($IC_{50} = 0.430$ mg/mL) of water extracts of housefly larvae (*Musca domestica*) (Li et al., 2017). Similarly, small peptides (<3kDa) from shrimp (*Pandalopsis dispar*) byproducts produced by Alcalase and Protamex hydrolysis revealed strong ACE activity but were also associated with the adverse effect as bitterness (Cheung & Li-Chan, 2010).

Fermentation was shown as a good method for the production of ACE inhibitory peptides. In particular, fermentation of marine shrimp (*Acetes chinensis*) with *Lactobacillus fermentum* SM 605 resulted in the production of new ACE inhibitory peptides (Asp-Pro, Gly-Thr-Gly, and Ser-Thr) with an IC_{50} value of 3.37 mg/mL of fermented shrimp sauce (Wang et al., 2008). Other peptides Ser-Val and Ile-Phe obtained from Thai traditional fermented shrimp paste also exhibited ACE inhibitory activity (IC_{50} values of 60.68 and 70.03 μM, respectively) (Kleekayai et al., 2015). It is known, that insects can be fermented as well (Borremans, Lenaerts, Crauwels, Lievens, & Van Campenhout, 2018), but to the best of our knowledge there are no studies on ACE inhibitory potential of fermented insects.

It has been also shown, that bioactive hydrolysates can be obtained from a by-product of shrimp processes, such as shrimp shell discard (Ambigaipalan & Shahidi, 2017) and shrimp cooking juice (Pérez-Santín, Calvo, López-Caballero, Montero, & Gómez-Guillén, 2013) with the ACE inhibitory active peptides from 502 to 1355 Da in size for the latter. Protein-concentrated fractions from shrimp cooking wastewater obtained by ultrafiltration with 300, 100 and 30 kDa membranes showed potent ACE-inhibitory activities (IC_{50} values of 1.98, 9.87, and 23.10 μg/mL) comparable to other fish and seafood species (Amado, González, Murado, & Vázquez, 2016). Smaller peptides of <3, 3–10, and >10 kDa from northern shrimp by-products hydrolyzates showed IC_{50} values of 0.06, 0.03 and 0.03 mg/mL, respectively (Kim, Yoon, Shim, & Lim, 2016). Thus, proteins and peptides obtained from insects, shrimps, and their by-products have the potential for ACE inhibition.

4.1.1.1. Antioxidant activity. Compounds with antioxidant activities can scavenge free radicals and prevent the radical chain reactions of oxidation (Gülçin, 2012). It has been shown, that enzyme assisted hydrolysis of insects and shrimps leads to the production of peptides with antioxidant activity. The treatment of lesser mealworms with the metallo-protease thermolysin resulted in the release of active peptides from its isolate ($IC_{50} = 0.63$ mg/mL) and concentrate ($IC_{50} = 0.60$ mg/mL) (Lacroix, Dávalos Terán, Fogliano, & Wichers, 2018). Comparable antioxidant activity ($IC_{50} = 0.40$–1.01 mg/mL) was observed for protein hydrolysates from tropical banded crickets (*Gryllodes sigillatus*) after hydrolysis with Protamex (Nongonierma, Lamoureux, & FitzGerald, 2018). The potential of enzymatic hydrolysis using Alcalase and neutral proteinase to produce natural antioxidant food additives was also reported for houseflies (Zhang et al., 2016) and whiteleg shrimp (Ketnawa et al., 2016). Extract paste Mungoong prepared from raw cephalothorax of white shrimp with the addition of 0.15% Flavourzyme showed higher antioxidant activity, than paste prepared by other methods (Benjakul, Binsan, Visessanguan, Osako, & Tanaka, 2009).

The degree of hydrolysis significantly affected the antioxidant activity of hydrolysates of white shrimp prepared with Alcalase 2.4 L and Protamex. In particular, higher peptide chain hydrolysates had the highest antioxidant power for the DPPH and reducing power, while the lower peptide chain ones - higher antioxidant power for ABTS radical scavenging (Latorres, Rios, Saggiomo, Wasielesky, & Prentice-Hernandez, 2018). A similar trend was observed for hydrolysates from housefly larvae, i.e. the antioxidant activity was reported due to the presence of the low molecular weight constituents (<6 kDa), while DPP-IV inhibitory activity ($IC_{50} = 3.52$ mg/mL) was due to the high-molecular-weight constituents (>6 kDa) (Li et al., 2017).

Simulated gastrointestinal digestion of insect proteins led to the enhancement of bioactivity and was previously reported to cricket proteins (Hall, Johnson, & Liceaga, 2018), cricket, super worms (Zielińska, Karaś, & Jakubczyk, 2017), and silkworm larvae (Wu et al., 2011). These findings are promising for the potential beneficial effect of bioactive compounds released during natural digestive processes, but further *in vivo* model studies are needed.

Similar approaches for the production of peptide fractions from insects and shrimps with high ACE activity can be effective for enhancement of antioxidant activities, such as fermentation (Faithong, Benjakul, Phatcharat, & Binsan, 2010; Prapasuwannakul & Suwannahong, 2015).

Except for proteins, other constituents of insects and shrimps were reported to have antioxidant activity. Oil extracted from larvae of the beetle *Pachymerus nucleorum* exhibited antioxidant activity (24.3 uM Trolox/g) in addition to a high level of unsaturated fatty acids (Alves, Sanjinez Argandoña, Linzmeier, Cardoso, & Macedo, 2016). Mantis shrimp (*Oratosquilla nepa*) oil showed antioxidant activity with DPPH higher than olive and corn oils. It has been suggested that tocopherol (41.6–49.7 mg/100 g oil) and astaxanthin (1.9–2.8 g/100 g oil), which are known as antioxidants, may contribute to the observed effect, and astaxanthin provides red color to the shrimps (Chaijan & Panpipat, 2019).

Dietary carotenoids are known to have health benefits and may decrease the risk of disease, for example certain cancers and eye disease (Eggersdorfer & Wyss, 2018). In crustaceans, carotenoids are mainly absorbed from the diet (Sachindra, Bhaskar, & Mahendrakar, 2005). One of the red fat-soluble carotenoids found in crustaceans, astaxanthin is known to have antioxidant, anticancer properties, prevents diabetes and cardiovascular diseases (Ambati, Phang, Ravi, & Aswathanarayana, 2014; Vieira, Oliveira, & Kurozawa, 2016). The astaxanthin-rich fraction of carotenoid extract obtained from shrimp processing discards showed that its singlet oxygen quenching activity, ability to inhibit the thermal oxidation of phospholipid liposomes, and protection factor against singlet oxygen mediated oxidation of liposomes was higher than that of α-tocopherol (Sowmya & Sachindra, 2012). Astaxanthin and other carotene derivatives such as lycopene, β-carotene, zeaxanthin, violaxanthin, xanthophylls, and β-carotene monoepoxide were also detected in insects (Shamim, Ranjan, Pandey, & Ramani, 2014), but further studies should aim to explore their antioxidant potential.

Phenolic compounds and their values in house cricket and yellow mealworm extracts obtained after ultrasound-assisted and pressurized-liquid extractions using ethanol or ethanol:water (0.3–5.0 g gallic acid equivalent/100 g of extract) were found to be in correlation with antioxidant activity (del Hierro, Gutiérrez-Docio, Otero, Reglero, & Martin, 2020). Seymour et al. purified an antioxidant of phenolic nature from shrimp shell that was proposed as 1,2-diamino-1-(o-hydroxyphenyl)propene (Seymour, Li, & Morrissey, 1996). Furthermore, di Mattia et al. recently demonstrated that water-soluble extracts of grasshoppers, silkworm, and crickets have antioxidant capacity 5-fold higher than fresh orange juice (Di Mattia, Battista, Sacchetti, & Serafini, 2019), but the contribution of phenolic compounds needs further investigation.

The chitosan from the exoskeletons of insects and shrimps was reported to be a promising source of antioxidants, that contributes into valorization of processing waste streams (Mahdy Samar, El-Kalyoubi, Khalaf, & Abd El-Razik, 2013; Song, Yu, Zhang, Yang, & Zhang, 2013).

The facts stated above clearly indicate that both insect and shrimp hydrolysates, as well as carotenoids and phenolic compounds, represent a very promising source of readily available biologically active material. A number of methods with their advantages and shortcomings are currently used for the determination of antioxidant activities of insect and shrimp that complicated the comparison, therefore a more standardized approach should be developed and used.

4.1.1.2. Cardio-protective activity. Cardio-protective nature of shrimps was proposed due to atherogenic (AI) and thrombogenic (TI) indices (0.36 and 0.29, respectively), which are lower than in other nonvegetarian foods (Dayal et al., 2013). Similarly, low indexes of atherogenicity (0.32–0.36) and thrombogenicity (0.28–0.34) were observed for Atlantic white shrimp (*Litopenaeus schimitti*). These atherogenic indexes are lower than those for beef (0.72), pork (0.69), chicken (0.50), rabbit (0.82), and lamb (1.00) and related to the quality of lipids and their desirability (Pires et al., 2018). In this regard, a study by De Oliveira e Silva et al. showed that moderate shrimp consumption does not have an adverse effect on the overall lipoprotein profile of normolipidemic subjects (De Oliveira e Silva et al., 1996). Comparative analysis of AI and TI of mealworms demonstrated that the values of 0.6–0.7 and 1.2–1.4 for larvae of *Zophobas morio*, respectively, are higher than those for larvae and adults of *Tenebrio molitor* (0.3–0.5 for AI and 0.5–0.8 for TI) (Mlček et al., 2019), but were comparable to shrimps and conventional meat sources.

4.1.1.3. Anticarcinogenic activity. Both insects and shrimps contain compounds such as proteins, peptides, alkaloids or chitin that are effective against cancer. Insect proteins such as pierisins and lectins, and peptides such as alloferon 1 were shown to have potential anticancer activity (Slocinska, Marciniak, & Rosinski, 2008). The Texas grasshopper yielded three alkaloids pancratistatin, narciclasine, and ungeremine that were efficient inhibitors of several human cancer cell lines BXPC-3, MCF-7, SF268, NCI-H460, KM20L2, and DU-145 (Pettit, Meng, Herald, Knight, & Day, 2005). Also, crude insect-derived extracts were effective against HeLa cancer cell to various degrees of efficiency, with species as red ant (*Formica rufa*), scorpion (*Buthus martensi*), *Tabanus* sp, and vespae nidus (*Polistes mandarinus*) showing the most potent cytotoxicities (Ahn, Ryu, Lee, & Kim, 2000). On the other hand, peptide fractions from shrimp shell waste ranging from 10 to 30 kDa and $<$10 kDa inhibited the growth of Caco-2 and HepG2 cells by 60% while the fractions below 10 kDa inhibited the growth of HepG2 cells by 55% in comparison to control (Kannan, Hettiarachchy, Marshall, Raghavan, & Kristinsson, 2011).

Chitin, chitosan, and low molecular weight chitin from shrimp *Parapenaeus longirostris* had IC_{50} (μg/mL) values of 739, 531 and 1, respectively towards the human tumour cell line THP-1 (Salah et al., 2013). Finally, chitin and chitosan isolated from *Penaeus monodon* shells showed anticancer activity towards PA-1 cells in concentrations of 50 and 10 μg/mL (Srinivasan, Velayutham, & Ravichandran, 2018). This indicates that there is an untapped potential of insect and shrimp components in fighting cancer although more research is needed.

4.2. *In vivo studies*

In vivo studies that include anti-obesity, anti-hepatic steatosis, hypolipidemic, and hypocholesterolemic effects caused by oral administration of insects and shrimps by mice, rats, drosophilas, and humans, as well as the responses of gut microflora and effect on healthspan were previously reported (Table 3). In general, these studies are very valuable for the information they provide, but are far scarcer compared to those done *in vitro*. Nevertheless, the main outcomes of several interesting ones shall be discussed further.

4.2.1. *Anti-obesity effect*

Overweight and obesity have an adverse effect on health. Daily oral administration of yellow mealworm larvae powder at the concentrations of 100 mg/kg per day and 3000 mg/kg per day attenuated body weight gain of obese mice fed a high-fat diet and reduced hepatic steatosis (Seo et al., 2017). Follow-up studies revealed that yellow mealworm larvae extract administration suppressed feeding through down-regulating the expression of the orexigenic neuropeptides neuropeptide Y and agouti-related protein. Moreover, mealworm extract significantly reduced the expression of endoplasmic reticulum stress response genes (Seo, Kim, Moon, Hwang, & Kim, 2017). Promising anti-obesity activity of another insect Korean horn beetle (*Allomyrina dichotoma*) was demonstrated for extract using 3 T3-L1 cells as an *in vitro* model of adipogenesis (Chung, Yoon, Hwang, Goo, & Yun, 2014). The following study by Yoon et al. showed that its larvae reduced body weight gain, organ weight and

Table 3
In vivo studies of health benefits of insects and shrimps.

Latin name	Common name	Fraction	Preparation	Test organism	Dose	Major studied effect	References
Acheta domesticus	Cricket	Whole	Pasterization, drying	Rats	283.0 g/kg of the test diet	Body composition, hemoglobin	(Agbemafle, Hanson, Bries, & Reddy, 2019)
Allomyrina dichotoma	Korean horn beetle	Whole	Lyophilized	Mice	100 mg/kg per day, 3000 mg/kg per day	Anti-obesity effect	(Yoon et al., 2015)
Bombyx mori	Silkworm	Whole	Steaming, freeze-drying	Rats	0.1, 1 or 10 g/kg body weight	Hepatic steatosis, lipid metabolism	(Hong et al., 2018)
Bombyx mori	Silkworm	Whole	Boiling, freeze-drying	Drosophila	5, 10, and 20%	Healthspan, lifespan, resistance to Parkinson's disease	(Nguyen et al., 2016)
Gryllodes sigillatus	Cricket	Powder	Drying, roasting	Human	25 g/day	Gut microbiota	(Stull et al., 2018)
Rhynchophorus phoenicis fabricius	Palm weevil	Whole	Blanching, freeze-drying	Rats	403.0 g/kg of the test diet	Body composition, hemoglobin	(Agbemafle et al., 2019)
Tenebrio molitor	Yellow mealworm	Whole	Freeze-drying	Mice	100 mg/kg per day, 3000 mg/kg per day	Adipogenesis and anti-obesity effect	(Seo et al., 2017)
Tenebrio molitor	Yellow mealworm	Oil	Solid-liquid extraction	Rats	5000 mg/kg	Biochemical parameters	(Alves et al., 2019)
Pandalus borealis	Northern pink shrimp	Protein concentrate	Patent processing technology	Mice	35% and 70% of casein replacement	Oral glucose tolerance	(Wang et al., 2016)
Penaeus brasiliensis, Penaeus paulensis	Pink shrimp	Shrimp waste (head, carapace, tail)	Low pressure extraction, supercritical fluid extraction	Mice	50, 100 and 200 mg/kg per day	Anti-obesity and hypolipidemic effects	(Mezzomo et al., 2015)
Penaeus orientalis	Shrimp	Edible fraction	Freeze-drying, defatting	Mice	15% proteins of a basal diet	Serum and liver lipid levels	(Tanaka et al., 1998)
Penaeus sp.	Shrimp	Fermented shrimp-shell hydrolysate	Fermentation, freeze-drying	Rats	10%+cholesterol-rich basal diet	Hypocholesterolemic, antioxidant and prebiotic activity	(Halder et al., 2013)

adipose tissue volume of mice in a dose-dependent manner. Additionally, gene expression levels of transcription factors PPAR-gamma and CEBPA, and lipoprotein lipase in the epididymal fat tissue of high fat diet-fed mice with 3000 mg/kg per day insect powder were reduced by 12.4, 25.7, and 12.3 fold, respectively (Yoon et al., 2015).

Effectiveness in inhibition of lipase activity related to the digestion of dietary lipids, as a strategy against obesity and overweight, was also supported in the studies of the extracts from house crickets and yellow mealworms (del Hierro et al., 2020). Hypolipidemic and anti-obesity effects were also demonstrated in a 30-day experiment with high-fat diet combined with shrimp extracts (50–100 mg/kg day) (Mezzomo et al., 2015). Moreover, the replacement of dietary casein with shrimp protein in a diet-induced obese mouse model significantly improved levels of oral glucose tolerance and 4-hr fasting blood glucose. However, no effect was found on the levels of fasting blood glucose and insulin (Wang et al., 2016).

4.2.2. *Hypolipidemic activity*

Hyperlipidemia can cause the development of various cardiovascular diseases. Introduction of shrimps into the diet of mice showed the hypolipidemic activity, while the serum cholesterol-lowering activity was attributed to the lipid fraction, and reduction of hepatic cholesterol and an increase of faecal steroid – to a non-lipid fraction (Tanaka, Sakai, Ikeda, Imaizumi, & Sugano, 1998). It has been stated, that hydrolysates from shells of *Penaeus* sp. shrimps have a hypocholesterolemic effect, they can resist lipid peroxidation and affect the growth of health beneficial microbes in male albino rats, and therefore can be promising for hypercholesterolemic patients as a functional food (Halder et al., 2013). However, it is still little known, what exactly causes the hypolipidemic activity in cases described above.

The lipid metabolism of rats was affected by silkworm chrysalis oil, rich in n-3 a-linolenic acid, that allowed to suggest that silkworm chrysalis oil can improve hyperlipidaemia and hyperglycaemia (Mentang, Maita, Ushio, & Ohshima, 2011). Furthermore, chitooligosaccharides obtained from chitosan of *Clanis bilineata* larvae skin decreased body weight gain, plasma triacylglycerol, total cholesterol, and plasma low-density lipoprotein cholesterol levels in Sprague-Dawley rats. In the same study, the faecal fat and cholesterol were higher in rats fed a diet with chitooligosaccharides, that demonstrates their potential as an alterative hypolipidemic source for humans (Xia, Chen, & Wu, 2013).

4.2.3. *Anti-hepatic steatosis activity*

Hepatic steatosis is an early-stage disorder in alcoholic liver disease. Hong et al. demonstrated that steamed and freeze-dried silkworm larval powder supplementation is effective in preventing hepatic steatosis and injury in ethanol-treated rats through increase fatty acid β-oxidation, decrease *de novo* synthesis of fatty acids and collagen fiber, and inhibition of oxidative stress and inflammatory response (Hong et al., 2018).

4.2.4. *Effect on gut microflora*

The study of the consumption effect of 25 g of whole cricket powder per day on gut microbiota revealed tolerance and non-toxicity of crickets for the studied dose. Cricket powder supported the growth of the probiotic bacterium *Bifidobacterium animalis* and reduced plasma TNF-α, thus eating crickets may improve gut health and lower systemic inflammation (Stull et al., 2018). Using an *in vitro* faecal model, Mota de Carvalho et al. demonstrated a positive impact of digested yellow mealworm flour on gut microbiota through an increase and/or upkeep of health-promoting bacterial groups (de Carvalho et al., 2019).

4.2.5. *Effect on health-span*

Rearing of *Drosophila* sp. on food containing boiled and freeze-dried mature silkworm larval powder demonstrated a significant increase in health-span, lifespan, and resistance to rotenone-induced Parkinson's disease symptoms in comparison to control flies (Nguyen et al., 2016).

5. Safety aspects of insect and shrimp consumption

Evaluation of the safety of insects and shrimps as a food source is a key factor surrounding their consumption and farming. Insects and shrimps accumulate toxic materials from the environment they are farmed in. For instance, insect collection from the wild not only negatively affects biodiversity but also increases the risk of contamination with pesticides and heavy metals (van Huis et al., 2013). As an alternative to wild harvesting, the recent development of rearing systems with a control environment and diet significantly lower the possible contamination.

Another important safety aspect is the presence of toxic and allergic substances. There is still a limited number of studies on the possible toxicity of insects through oral administration. Gao et al. reviewed 34 edible insects in China and demonstrated that most of the studied insects are non-toxic (Gao, Wang, Xu, Shi, & Xiong, 2018). The recent study by Alves et al. showed that oils from yellow mealworm and coconut borer (*Pachymerus nucleorum*) favored a reduction in cholesterol and glucose levels in the rats, while safety evaluation showed low toxicity of oils and did not cause lethality and changes in haematological parameters of rats (Alves et al., 2019). The promising results were obtained for *Allomyrina dichotoma* larvae demonstrating not mutagenic or clastogenic effects *in vitro* and *in vivo* genotoxicity tests, and additional 28-day oral toxicity study showed that the freeze-dried larvae can be considered to have No Observed Adverse Effect Level (NOAEL) of 2500 mg/kg/day or more for both sexes of Sprague-Dawley rats (Noh et al., 2015). Similar results were obtained for the safety assessment of freeze-dried larvae of yellow mealworm, i.e. NOAEL was determined to be more than 3000 mg/kg/day for male and female of Sprague-Dawley rats in a 90-day experiment (Han et al., 2016). After oral administration of white-spotted flower chafer (*Protaetia brevitarsis*) at a dose of 300, 1000, and 3000 mg/kg/day for 13 weeks, no adverse effects or changes in mortality, clinical observations, food consumption, clinical pathology, histopathology and other parameters were observed in rats (Noh et al., 2018).

Crustaceans are well known to cause an allergic reaction (Ruethers et al., 2018), that is also relevant to insect species. It has been recently shown that the cricket allergen, namely tropomyosin, may induce an allergic reaction in individuals with allergy to crustacean, that should be taken into account before insect consumption (Kamemura et al., 2019). However, insect processing by enzymatic and thermal approaches can reduce the risk of cross-reactivity and allergenicity in patients allergic to crustaceans and house dust mite (Linnemann et al., 2019). Moreover, the increase of the degree of hydrolysis to 60–85% decreased IgE reactivity to tropomyosin, as it has been demonstrated for crickets (Hall et al., 2018). Boiling, roasting, and steaming of shrimps were reported to not be sufficient to lower tropomyosin concentrations (Usui et al., 2015), but high-intensity ultrasound at 50 °C showed the reduction in allergenicity of shrimps (Zhenxing, Caolimin, & Jamil, 2006). Future studies should focus on the impact of both shrimp and insect to the oral consumption in regards to the allergenic and toxic reaction to the consumers.

Given the fact that insects can be consumed whole or as insect powder that contains chitin, the digestibility of chitin is an important factor to consider for the elimination of possible adverse health consequences. It has been shown, that humans have enzymes with chitinolytic activities, namely chitotriosidase (Chit1) and acidic mammalian chitinase (AMCase) (Ohno et al., 2013). However, their activity might be very low for those who do not consume food containing chitin regularly (Paoletti, Norberto, Damini, & Musumeci, 2007).

Shrimp and fish are valuable sources of iodine and it has been demonstrated that relatively increased consumption of fish does not appreciably increase the risk of thyroid cancer (Bosetti et al., 2001). Iodine concentration in whole raw shrimps was determined at 3.96–4.09 μg/g of dried weight while cooking decreased iodine concentration in whole shrimps and shrimp tissue by about 26-27 and 40%, respectively (Mesko et al., 2016). In comparison, larvae of soldier flies and nymphs of Turkestan cockroach (*Blatta lateralis*) had 0.26 and 0.30 mg/kg of iodine, while in larvae of Tebo worms (*Chilecomadia moorei*) and adult house flies iodine was at the concentration of <0.1 mg/kg (Finke, 2013), but more studies about iodine in insects are needed in future.

It is safe to conclude that both insects and shrimps are a viable source of food, although more studies involving models with oral intake are needed to bridge the knowledge gap and ensure that they are considered as a safe and functional food type.

6. Perspectives for insect and shrimp based functional foods

Based on the foregoing, insects and shrimps can be classified as a good, and at some extent unexplored, source of nutrients and bioactive compounds applicable for a wide range of functional food ingredients and food supplements. Upon their characteristics, they can be specifically utilized as a functional food component for a specific purpose. Moreover, the potential of additional health-promoting properties of insects and shrimps can be altered through the processing and formulation of value-added products, that should be taken into account and tailor-made for a specific material.

Pretreatment is required for insects and shrimps derived materials in order to decrease microbial load and provide safety, but conventional treatments can cause negative side effects affecting the activity of functional components. In particular, a way of cooking was determined to affect the amino acid composition in Southern pink shrimp (*Penaeus notialis*) by an increase of leucine to 102 mg/g protein in smoked products (Akintola, 2015). Heat treatments such as baking generally increased ABTS and DPPH scavenging activities of crickets (Zielińska, Baraniak, & Karaś, 2017). Moreover, heat involved processing may reduce total phenolic and flavonoids, as it has been demonstrated for stinkbugs (Musundire, Zvidzai, & Chidewe, 2014) and lead to decomposition of carotenoids and decrease of the antioxidant activities in shrimp shells (Lira, Lopez, Firmino, Santos, & de Bezerra, 2017). In this regard, the effect of pretreatment on the degradation of functional elements should be considered along with the changes in nutritional values, digestibility, and sensory properties.

While shrimps are a known meat source, insects are a new food source for a large portion of consumers in the Western world. Due to their low acceptability and natural neophobic attitude and even prejudice towards insects, the type of insect-based food and a way of insect incorporation is important to consider. Insects are recently claimed as a promising meat substitute due to high protein content, that is comparable to conventional meat sources as beef and pork. Additionally, some insect species such as larvae of mealworm and superworm have low purine content and can be recommended as meat alternatives (Bednářová, Borkovcová, & Komprda, 2014). Designing of meat-like structures from insects and application of ultra-processing technologies require assessment of their influence on the degradation of functional compounds, changes in their properties, and alternative mild processing technologies should be explored.

Besides meat, shrimp by-products were reported to have the potential for the development of new ingredients and products such as flour, biscuits, soup, pastry (Fernandes, da Silva, da Silva, Cavalheiro, & da Conceição, 2013; Gonçalves & dos Santos Junior, 2019). Similarly, insects can be used for the fortification of pasta, protein bars, powdered peanut butter, crackers, biscuits, tortillas, burgers, bread, granola bars, sauces, ravioli (Melgar-Lalanne, Hernández-Álvarez, & Salinas-Castro, 2019). However, further upscaling of its production is still required for making these insect derived foods commercially viable.

Fermentation is one of the traditional processing methods of shrimps into fermented products, such as pastes. As has been discussed earlier, fermentation may lead to the production of highly functional peptides, but the known benefits of fermented foods are much wider including prevention of cardiovascular disease, cancer, gastrointestinal and other disorders (Tamang, Shin, Jung, & Chae, 2016). Future development of fermented insect and shrimp derived foods, especially from their by-products, might widen the spectrum of novel food with additional health benefits on Western market.

Hydrolysates from insects and shrimps possess antioxidant activity, that can be used for fortification of beverages, such as protein and sports drinks, providing additionally enhanced digestibility. Due to health-associated risks of hydrogenated trans-fats, new materials for substitution of milk and plant lipids are required. A recent study showed that black soldier fly and yellow mealworm can be used to substitute up to 75% of lipids in margarine providing lower environmental impact than butter (Smetana, Leonhardt, Kauppi, Pajic, & Heinz, 2020). Effect of incorporation of insect fat (that can be less relevant for shrimps due to low fat content) into conventional food products on human health should be investigated in future.

Thus, further development of products with insects and shrimps should consider not only their nutritional values, microbiological safety, and sensory properties, but also their bioactivities and mechanisms of action that will deepen our understanding and will be beneficial for incorporating them into novel functional food formulations.

7. Conclusion

Several interesting facts and findings of health-promoting benefits of insects and shrimps consumption are elaborated upon in this review. Firstly, it has been shown that insects and shrimps both represent unique sources of food with high nutritional value especially in terms of protein content and amino acid composition, while hydrolyzates of insects and shrimps are potential in angiotensin-converting enzyme inhibitory and antioxidant activities. Secondly, the fat of shrimps can be considered "healthy" due to a high amount of unsaturated fatty acids, omega-6/omega-3 ratio, and a relatively low level of cholesterol however insect fat has less favourable omega-6/omega-3 ratio. Shrimps have an extremely low amount of fat (~1%), while insect fat can be fractionated and used as a separate food ingredient. Thirdly, the amount of vitamins and minerals present in insects and shrimps makes them a valuable source and promising functional food or supplement. Also, insects have the potential to be used in low-sodium diets. Fourthly, insects and shrimps express antioxidant activities, especially, due to the presence of phenolic compounds and carotenoids. Future studies should further explore the potential of carotenoids, especially astaxanthin. Taking into consideration all facts mentioned here, it is reasonable to conclude that insects and shrimps meet the criteria to be considered as future functional food ingredients. However more *in vitro*, as well, *in vivo* and clinical studies are needed along with oral intake safety and allergy assessment.

Ethical statement

(1) This material is the authors' own original work, which has not been previously published elsewhere.
(2) The paper is not currently being considered for publication elsewhere.
(3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
(4) The paper properly credits the meaningful contributions of co-authors.
(5) The results are appropriately placed in the context of prior and existing research.
(6) All sources used are properly disclosed.
(7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Agbemafle, I., Hanson, N., Bries, A. E., & Reddy, M. B. (2019). Alternative protein and iron sources from edible insects but not *Solanum torvum* improved body composition and iron status in malnourished rats. *Nutrients, 11*, 2481. https://doi.org/10.3390/nu11102481.

Ahn, M. Y., Ryu, K. S., Lee, Y. W., & Kim, Y. S. (2000). Cytotoxicity and L-amino acid oxidase activity of crude insect drugs. *Archives of Pharmacal Research, 23*(5), 477–481. https://doi.org/10.1007/BF02976576.

Akintola, S. L. (2015). Effects of smoking and sun-drying on proximate, fatty and amino acids compositions of Southern pink shrimp (*Penaeus notialis*). *Journal of Food Science and Technology, 52*(5), 2646–2656. https://doi.org/10.1007/s13197-014-1303-0.

Alves, A. V., Freitas de Lima, F., Granzotti da Silva, T., Soares de Oliveira, V., Leite Kassuya, C. A., & Sanjinez-Argandoña, E. J. (2019). Safety evaluation of the oils extracted from edible insects (*Tenebrio molitor* and *Pachymerus nucleorum*) as novel food for humans. *Regulatory Toxicology and Pharmacology, 102*, 90–94. https://doi.org/10.1016/J.YRTPH.2019.01.013.

Alves, A. V., Sanjinez Argandoña, E. J., Linzmeier, A. M., Cardoso, C. A. L., & Macedo, M. L. R. (2016). Chemical composition and food potential of *Pachymerus nucleorum* larvae parasitizing *Acrocomia aculeata* kernels. *PLoS ONE, 11*(3), 1–9. https://doi.org/10.1371/journal.pone.0152125.

Amado, I. R., González, M. P., Murado, M. A., & Vázquez, J. A. (2016). Shrimp wastewater as a source of astaxanthin and bioactive peptides. *Journal of Chemical Technology and Biotechnology, 91*(3), 793–805. https://doi.org/10.1002/jctb.4647.

Ambati, R. R., Phang, S. M., Ravi, S., & Aswathanarayana, R. G. (2014). Astaxanthin: Sources, extraction, stability, biological activities and its commercial applications - A review. *Marine Drugs, 12*, 128–152. https://doi.org/10.3390/md12010128.

Ambigaipalan, P., & Shahidi, F. (2017). Bioactive peptides from shrimp shell processing discards: Antioxidant and biological activities. *Journal of Functional Foods, 34*, 7–17. https://doi.org/10.1016/j.jff.2017.04.013.

Arai, S. (2005). Functional food science. *Journal of the Science of Food and Agriculture, 85* (10), 1603–1605. https://doi.org/10.1002/jsfa.2248.

Bednářová, M., Borkovcová, M., & Komprda, T. (2014). Purine derivate content and amino acid profile in larval stages of three edible insects. *Journal of the Science of Food and Agriculture, 94*, 71–76. https://doi.org/10.1002/jsfa.6198.

Behmer, S. T., & Nes, W. D. (2003). Insect sterol nutrition and physiology: A global overview. *Advances in Insect Physiology, 31*, 1–72. https://doi.org/10.1016/S0065-2806(03)31001-X.

Benjakul, S., Binsan, W., Visessanguan, W., Osako, K., & Tanaka, M. (2009). Effects of flavourzyme on yield and some biological activities of Mungoong, an extract paste from the cephalothorax of white shrimp. *Journal of Food Science, 74*(2). https://doi.org/10.1111/j.1750-3841.2009.01055.x.

Borremans, A., Lenaerts, S., Crauwels, S., Lievens, B., & Van Campenhout, L. (2018). Marination and fermentation of yellow mealworm larvae (*Tenebrio molitor*). *Food Control, 92*, 47–52. https://doi.org/10.1016/J.FOODCONT.2018.04.036.

Bosetti, C., Kolonel, L., Negri, E., Ron, E., Franceschi, S., Maso, L. D., … Vecchia, C. L. (2001). A pooled analysis of case-control studies of thyroid cancer. VI. Fish and shellfish consumption. *Cancer Causes and Control, 12*, 375–382. https://doi.org/10.1023/A:1011267123398.

Budd, G. E., & Telford, M. J. (2009). The origin and evolution of arthropods. *Nature, 457* (7231), 812–817. https://doi.org/10.1038/nature07890.

Cankiriligil, E. C., & Berik, N. (2017). Changes in fatty acid and mineral compositions of rose-shrimp croquettes during production process. *American Journal of Food Technology, 12*, 254–261. https://doi.org/10.3923/ajft.2017.254.261.

Chaijan, M., & Panpipat, W. (2019). Basic composition, antioxidant activity and nanoemulsion behavior of oil from mantis shrimp (*Oratosquilla nepa*). *Food Bioscience, 31*, Article 100448. https://doi.org/10.1016/j.fbio.2019.100448.

Chamberlain, G. W. (2012). History of shrimp farming. In V. Alday-Sanz (Ed.), *The Shrimp Book* (pp. 1–38). UK: Nottingham University Press.

Cheung, I. W. Y., & Li-Chan, E. C. Y. (2010). Angiotensin-I-converting enzyme inhibitory activity and bitterness of enzymatically-produced hydrolysates of shrimp (*Pandalopsis dispar*) processing byproducts investigated by Taguchi design. *Food Chemistry, 122*, 1003–1012. https://doi.org/10.1016/j.foodchem.2010.03.057.

Chung, M. Y., Yoon, Y.-I., Hwang, J.-S., Goo, T.-W., & Yun, E.-Y. (2014). Anti-obesity effect of *Allomyrina dichotoma* (Arthropoda: Insecta) larvae ethanol extract on 3T3-L1 adipocyte differentiation. *Entomological Research, 44*, 9–16. https://doi.org/10.1111/1748-5967.12044.

Cito, A., Botta, M., Francardi, V., & Dreassi, E. (2017). Insects as source of angiotensin converting enzyme inhibitory peptides. *Journal of Insects as Food and Feed, 3*(4), 231–240. https://doi.org/10.3920/jiff2017.0017.

Costa-Neto, E. M. (2005). Entomotherapy, or the medicinal use of insects. *Journal of Ethnobiology, 25*(1), 93–114.

Dang, T. T., Gringer, N., Jessen, F., Olsen, K., Bøknæs, N., Nielsen, P. L., & Orlien, V. (2018). Emerging and potential technologies for facilitating shrimp peeling: A review. *Innovative Food Science and Emerging Technologies, 45*, 228–240. https://doi.org/10.1016/j.ifset.2017.10.017.

Dayal, J. S., Ponniah, A. G., Khan, H. I., Babu, E. P. M., Ambasankar, K., & Vasagam, K. P. K. (2013). Shrimps - a nutritional perspective. *Current Science, 104* (11), 1487–1491.

de Carvalho, N. M., Walton, G. E., Poveda, C. G., Silva, S. N., Amorim, M., Madureira, A. R., … Jauregi, P. (2019). Study of in vitro digestion of *Tenebrio molitor* flour for evaluation of its impact on the human gut microbiota. *Journal of Functional Foods, 59*, 101–109. https://doi.org/10.1016/J.JFF.2019.05.024.

De Oliveira e Silva, E. R., Seidman, C. E., Tian, J. J., Hudgins, L. C., Sacks, F. M., & Breslow, J. L. (1996). Effects of shrimp consumption on plasma lipoproteins. *The American Journal of Clinical Nutrition, 64*, 712–717.

del Hierro, J. N., Gutiérrez-Docio, A., Otero, P., Reglero, G., & Martin, D. (2020). Characterization, antioxidant activity, and inhibitory effect on pancreatic lipase of extracts from the edible insects *Acheta domesticus* and *Tenebrio molitor*. *Food Chemistry, 309*. https://doi.org/10.1016/J.FOODCHEM.2019.125742.

Desmond, E. (2006). Reducing salt: A challenge for the meat industry. *Meat Science, 74*, 188–196. https://doi.org/10.1016/j.meatsci.2006.04.014.

Di Mattia, C., Battista, N., Sacchetti, G., & Serafini, M. (2019). Antioxidant activities in vitro of water and liposoluble extracts obtained by different species of edible insects and invertebrates. *Frontiers in Nutrition, 6*, 106. https://doi.org/10.3389/fnut.2019.00106.

Doyon, M., & Labrecque, J. A. (2008). Functional foods: A conceptual definition. *British Food Journal, 110*(11), 1133–1149. https://doi.org/10.1108/00070700810918036.

Eggersdorfer, M., & Wyss, A. (2018). Carotenoids in human nutrition and health. *Archives of Biochemistry and Biophysics, 652*, 18–26. https://doi.org/10.1016/j.abb.2018.06.001.

Faithong, N., Benjakul, S., Phatcharat, S., & Binsan, W. (2010). Chemical composition and antioxidative activity of Thai traditional fermented shrimp and krill products. *Food Chemistry, 119*, 133–140. https://doi.org/10.1016/j.foodchem.2009.06.056.

Fernandes, T. M., da Silva, J. A., da Silva, A. H. A., Cavalheiro, J. M. de O., & da Conceição, M. L. (2013). Flour production from shrimp by-products and sensory evaluation of flour-based products. *Pesquisa Agropecuaria Brasileira, 48*(8), 962–967. https://doi.org/10.1590/S0100-204X2013000800022.

Finke, M. D. (2002). Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biology, 21*, 269–285. https://doi.org/10.1002/zoo.10031.

Finke, M. D. (2007). Estimate of chitin in raw whole insects. *Zoo Biology, 26*, 105–115.

Finke, M. D. (2013). Complete nutrient content of four species of feeder insects. *Zoo Biology, 32*(1), 27–36. https://doi.org/10.1002/zoo.21012.

Food and Agriculture Organization of the United Nations (2016). FAO/INFOODS Global Food Composition Database for Fish and Shellfish Version 1.0-uFiSh1.0. Rome, Italy.

Gao, Y., Wang, D., Xu, M.-L., Shi, S.-S., & Xiong, J.-F. (2018). Toxicological characteristics of edible insects in China: A historical review. *Food and Chemical Toxicology, 119*, 237–251. https://doi.org/10.1016/J.FCT.2018.04.016.

Ghosh, S., Lee, S. M., Jung, C., & Meyer-Rochow, V. B. (2017). Nutritional composition of five commercial edible insects in South Korea. *Journal of Asia-Pacific Entomology, 20* (2), 686–694. https://doi.org/10.1016/j.aspen.2017.04.003.

Gillett, R. (2008). Global study of shrimp fisheries. Rome.

Gonçalves, A. A., & dos Santos Junior, J. (2019). Shrimp processing residue as an alternative ingredient for new product development. *International Journal of Food Science and Technology, 54*(9), 2736–2744. https://doi.org/10.1111/ijfs.14184.

Guclu-Ustundag, Ö., & Mazza, G. (2007). Saponins: Properties, applications and processing. *Critical Reviews in Food Science and Nutrition, 47*(3), 231–258. https://doi.org/10.1080/10408390600698197.

Gülçin, I. (2012). Antioxidant activity of food constituents: An overview. *Archives of Toxicology, 86*(3), 345–391. https://doi.org/10.1007/s00204-011-0774-2.

Halder, S. K., Adak, A., Maity, C., Jana, A., Das, A., Paul, T., … Mondal, K. C. (2013). Exploitation of fermented shrimp-shells hydrolysate as functional food: Assessment of antioxidant, hypocholesterolemic and prebiotic activities. *Indian Journal of Experimental Biology, 51*, 924–934.

Hall, F., Johnson, P. E., & Liceaga, A. (2018). Effect of enzymatic hydrolysis on bioactive properties and allergenicity of cricket (*Gryllodes sigillatus*) protein. *Food Chemistry, 262*, 39–47. https://doi.org/10.1016/j.foodchem.2018.04.058.

Han, S.-R., Lee, B.-S., Jung, K.-J., Yu, H.-J., Yun, E.-Y., Hwang, J. S., & Moon, K.-S. (2016). Safety assessment of freeze-dried powdered *Tenebrio molitor* larvae (yellow mealworm) as novel food source: Evaluation of 90-day toxicity in Sprague-Dawley rats. *Regulatory Toxicology and Pharmacology, 77*, 206–212. https://doi.org/10.1016/j.yrtph.2016.03.006.

Heu, M.-S., Kim, J.-S., & Shahidi, F. (2003). Components and nutritional quality of shrimp processing by-products. *Food Chemistry, 82*, 235–242. https://doi.org/10.1016/S0308-8146(02)00519-8.

Hong, K.-S., Yun, S.-M., Cho, J.-M., Lee, D.-Y., Ji, S.-D., Son, J.-G., & Kim, E.-H. (2018). Silkworm (*Bombyx mori*) powder supplementation alleviates alcoholic fatty liver disease in rats. *Journal of Functional Foods, 43*, 29–36. https://doi.org/10.1016/j.jff.2018.01.018.

Inanli, A. G., Tümerkan, E. T. A., El Abed, N., Regenstein, J. M., & Özogul, F. (2020). The impact of chitosan on seafood quality and human health: A review. *Trends in Food Science and Technology, 97*, 404–416. https://doi.org/10.1016/j.tifs.2020.01.029.

Iwaniak, A., Minkiewicz, P., & Darewicz, M. (2014). Food-originating ACE inhibitors, including antihypertensive peptides, as preventive food components in blood pressure reduction. *Comprehensive Reviews in Food Science and Food Safety, 13*, 114–134. https://doi.org/10.1111/1541-4337.12051.

Jeepipalli, S. P. K., Du, B., Sabitaliyevich, U. Y., & Xu, B. (2020). New insights into potential nutritional effects of dietary saponins in protecting against the development of obesity. *Food Chemistry, 318*, Article 126474. https://doi.org/10.1016/j.foodchem.2020.126474.

Ji, S.-D., Nguyen, P., Yoon, S.-M., Kim, K.-Y., Son, J. G., Kweon, H., & Koh, Y. H. (2017). Comparison of nutrient compositions and pharmacological effects of steamed and freeze-dried mature silkworm powders generated by four silkworm varieties. *Journal of Asia-Pacific Entomology, 20*, 1410–1418. https://doi.org/10.1016/j.aspen.2017.10.010.

Kamemura, N., Sugimoto, M., Tamehiro, N., Adachi, R., Tomonari, S., Watanabe, T., & Mito, T. (2019). Cross-allergenicity of crustacean and the edible insect *Gryllus bimaculatus* in patients with shrimp allergy. *Molecular Immunology, 106*, 127–134. https://doi.org/10.1016/j.molimm.2018.12.015.

Kannan, A., Hettiarachchy, N. S., Marshall, M., Raghavan, S., & Kristinsson, H. (2011). Shrimp shell peptide hydrolysates inhibit human cancer cell proliferation. *Journal of the Science of Food and Agriculture, 91*, 1920–1924. https://doi.org/10.1002/jsfa.4464.

Kelemu, S., Niassy, S., Torto, B., Fiaboe, K., Affognon, H., Tonnang, H., … Ekesi, S. (2015). African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. *Journal of Insects as Food and Feed, 1*(2), 103–119. https://doi.org/10.3920/jiff2014.0016.

Ketnawa, S., Martínez-Alvarez, O., Gómez-Estaca, J., Del Carmen Gómez-Guillén, M., Benjakul, S., & Rawdkuen, S. (2016). Obtaining of functional components from cooked shrimp (*Penaeus vannamei*) by enzymatic hydrolysis. *Food Bioscience, 15*, 55–63. https://doi.org/10.1016/j.fbio.2016.05.005.

Kim, S.-B., Yoon, N. Y., Shim, K.-B., & Lim, C.-W. (2016). Antioxidant and angiotensin I-converting enzyme inhibitory activities of northern shrimp (*Pandalus borealis*) by-products hydrolysate by enzymatic hydrolysis. *Fisheries and Aquatic Sciences, 19*(29), 1–6. https://doi.org/10.1186/S41240-016-0028-6.

Kleekayai, T., Harnedy, P. A., O'Keeffe, M. B., Poyarkov, A. A., CunhaNeves, A., Suntornsuk, W., & FitzGerald, R. J. (2015). Extraction of antioxidant and ACE inhibitory peptides from Thai traditional fermented shrimp pastes. *Food Chemistry, 176*, 441–447. https://doi.org/10.1016/j.foodchem.2014.12.026.

Kumar, V., Sinha, A. K., Romano, N., Allen, K. M., Bowman, B. A., Thompson, K. R., & Tidwell, J. H. (2018). Metabolism and nutritive role of cholesterol in the growth, gonadal development, and reproduction of crustaceans. *Reviews in Fisheries Science and Aquaculture, 26*(2), 254–273. https://doi.org/10.1080/23308249.2018.1429384.

Kunatsa, Y., Chidewe, C., & Zvidzai, C. J. (2020). Phytochemical and anti-nutrient composite from selected marginalized Zimbabwean edible insects and vegetables. *Journal of Agriculture and Food Research, 2*, Article 100027. https://doi.org/10.1016/j.jafr.2020.100027.

Lacroix, I. M. E., Dávalos Terán, I., Fogliano, V., & Wichers, H. J. (2018). Investigation into the potential of commercially available lesser mealworm (*A. diaperinus*) protein to serve as sources of peptides with DPP-IV inhibitory activity. *International Journal of Food Science & Technology, 1–9*. https://doi.org/10.1111/ijfs.13982.

Latorres, J. M., Rios, D. G., Saggiomo, G., Wasielesky, J. W., & Prentice-Hernandez, C. (2018). Functional and antioxidant properties of protein hydrolysates obtained from white shrimp (*Litopenaeus vannamei*). *Journal of Food Science and Technology, 55*(2), 721–729. https://doi.org/10.1007/s13197-017-2983-z.

Latunde-Dada, G. O., Yang, W., & Vera Aviles, M. (2016). In vitro iron availability from insects and sirloin beef. *Journal of Agricultural and Food Chemistry, 64*(44), 8420–8424. https://doi.org/10.1021/acs.jafc.6b03286.

Lecocq, T. (2018). Insects: the disregarded domestication histories. In Animal domestication (pp. 35–68). Fabrice Teletchea: IntechOpen.

Lehtovaara, V. J., Valtonen, A., Sorjonen, J., Hiltunen, M., Rutaro, K., Malinga, G. M., … Roininen, H. (2017). The fatty acid contents of the edible grasshopper *Ruspolia differens* can be manipulated using artificial diets. *Journal of Insects as Food and Feed, 3*(4), 253–262. https://doi.org/10.3920/jiff2017.0018.

Li, H., Inoue, A., Taniguchi, S., Yukutake, T., Suyama, K., Nose, T., & Maeda, I. (2017). Multifunctional biological activities of water extract of housefly larvae (*Musca domestica*). *PharmaNutrition, 5*, 119–126.

Liland, N. S., Biancarosa, I., Araujo, P., Biemans, D., Bruckner, C. G., Waagbø, R., … Lock, E. J. (2017). Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. *PLoS ONE, 12*(8), 1–23. https://doi.org/10.1371/journal.pone.0183188.

Linnemann, D. E. S. L., Meinlschmidt, P., Purschke, B., Hofstetter, G., Rodríguez Monroy, F. A., Einhorn, L., … Pali-Schoell, I. (2019). Novel foods: Enzymatic and thermal food processing make edible insects non-allergenic. *Journal of Allergy and Clinical Immunology, 143*(2), AB35.

Lira, G. M., Lopez, A. M. Q., Firmino, G. O., Santos, S. D., & de Bezerra, R. de S. (2017). Total carotenoids and antioxidant activity of fillets and shells (in natura or cooked) of "Vila Franca" shrimp (*Litopenaeus schmitti*) in different intervals of storage under freezing. *Ciência e Agrotecnologia, 41*(1), 94–103. https://doi.org/10.1590/1413-70542017411023616.

Liu, S., Sun, J., Yu, L., Zhang, C., Bi, J., Zhu, F., … Yang, Q. (2012). Antioxidant activity and phenolic compounds of *Holotrichia parallela* Motschulsky extracts. *Food Chemistry, 134*(4), 1885–1891. https://doi.org/10.1016/J.FOODCHEM.2012.03.091.

Maezaki, Y., Yamazaki, A., Mizuochi, K., & Tsuji, K. (1993). Measurement of dietary fiber in chitin and chitosan by the enzymatic-gravimetric method. *Nippon Nogeikagaku Kaishi, 67*(4), 677–684. https://doi.org/10.1271/nogeikagaku1924.67.677.

Mahdy Samar, M., El-Kalyoubi, M. H., Khalaf, M. M., & Abd El-Razik, M. M. (2013). Physicochemical, functional, antioxidant and antibacterial properties of chitosan extracted from shrimp wastes by microwave technique. *Annals of Agricultural Science, 58*(1), 33–41. https://doi.org/10.1016/j.aoas.2013.01.006.

Melgar-Lalanne, G., Hernández-Álvarez, A., & Salinas-Castro, A. (2019). Edible insects processing: Traditional and innovative technologies. *Comprehensive Reviews in Food Science and Food Safety, 18*, 1166–1191. https://doi.org/10.1111/1541-4337.12463.

Mentang, F., Maita, M., Ushio, H., & Ohshima, T. (2011). Efficacy of silkworm (*Bombyx mori* L.) chrysalis oil as a lipid source in adult Wistar rats. *Food Chemistry, 127*, 899–904. https://doi.org/10.1016/j.foodchem.2011.01.045.

Mente, E., Coutteau, P., Houlihan, D., Davidson, I., & Sorgeloos, P. (2002). Protein turnover, amino acid profile and amino acid flux in juvenile shrimp *Litopenaeus vannamei*: Effects of dietary protein source. *Journal of Experimental Biology, 205*, 3107–3122.

Mesko, M. F., Toralles, I. G., Hartwig, C. A., Coelho, G. S., Muller, A. L. H., Bizzi, C. A., & Mello, P. A. (2016). Bromine and iodine contents in raw and cooked shrimp and its parts. *Journal of Agricultural and Food Chemistry, 64*, 1817–1822. https://doi.org/10.1021/acs.jafc.5b05769.

Mezzomo, N., Tenfen, L., Farias, M. S., Friedrich, M. T., Pedrosa, R. C., & Ferreira, S. R. S. (2015). Evidence of anti-obesity and mixed hypolipidemic effects of extracts from pink shrimp (*Penaeus brasiliensis* and *Penaeus paulensis*) processing residue. *Journal of Supercritical Fluids, 96*, 252–261. https://doi.org/10.1016/j.supflu.2014.09.021.

Mishyna, M., Martinez, J. J. I., Chen, J., & Benjamin, O. (2019). Extraction, characterization and functional properties of soluble proteins from edible grasshopper (Schistocerca gregaria) and honey bee (Apis mellifera). *Food Research International, 116*, 697–706. https://doi.org/10.1016/j.foodres.2018.08.098.

Mlček, J., Adámková, A., Adámek, M., Borkovcová, M., Bednářová, M., & Knížková, I. (2019). Fat from Tenebrionidae bugs – Sterols content, fatty acid profiles, and cardiovascular risk indexes. *Polish Journal of Food and Nutrition Sciences, 69*(3), 247–254. https://doi.org/10.31883/pjfns/109666.

Montowska, M., Kowalczewski, P. L., Rybicka, I., & Fornal, E. (2019). Nutritional value, protein and peptide composition of edible cricket powders. *Food Chemistry, 289*, 130–138. https://doi.org/10.1016/J.FOODCHEM.2019.03.062.

Mozaffarian, D., & Ludwig, D. S. (2015). The 2015 US Dietary Guidelines – Ending the 35% limit on total dietary fat. *JAMA, 313*(24), 2421–2422. https://doi.org/10.1001/jama.2015.5941.

Musundire, R., Osuga, I. M., Cheseto, X., Irungu, J., & Torto, B. (2016). Aflatoxin contamination detected in nutrient and anti-oxidant rich edible stink bug stored in recycled grain containers. *PLoS ONE, 11*(1), 1–16. https://doi.org/10.1371/journal.pone.0145914.

Musundire, R., Zvidzai, J. C., & Chidewe, C. (2014). Bio-active compounds composition in edible stinkbugs consumed in South-Eastern districts of Zimbabwe. *International Journal of Biology, 6*(3), 36–45. https://doi.org/10.5539/ijb.v6n3p36.

Nguyen, P., Kim, K.-Y., Kim, A.-Y., Kim, N.-S., Kweon, H., Ji, S.-D., & Koh, Y. H. (2016). Increased healthspan and resistance to Parkinson's disease in *Drosophila* by boiled and freeze-dried mature silk worm larval powder. *Journal of Asia-Pacific Entomology, 19*(2), 551–561. https://doi.org/10.1016/j.aspen.2016.05.003.

Noh, J.-H., Jeong, J.-S., Park, S.-J., Yun, E.-Y., Hwang, J. S., Kim, J.-Y., … Moon, K.-S. (2018). Toxicological safety evaluation of freeze-dried *Protaetia brevitarsis* larva powder. *Toxicology Reports, 5*, 695–703. https://doi.org/10.1016/J.TOXREP.2018.06.001.

Noh, J.-H., Yun, E.-Y., Kim, J.-Y., Lee, B.-S., Hwang, J. S., Jeong, E. J., & Moon, K.-S. (2015). Toxicological evaluation of genotoxicity and 28-day oral toxicity study on freeze-dried powder of *Allomyrina dichotoma* larvae. *Journal of Asia-Pacific Entomology, 18*(4), 807–813. https://doi.org/10.1016/j.aspen.2015.10.007.

Nongonierma, A. B., Lamoureux, C., & FitzGerald, R. J. (2018). Generation of dipeptidyl peptidase IV (DPP-IV) inhibitory peptides during the enzymatic hydrolysis of tropical banded cricket (*Gryllodes sigillatus*) proteins. *Food and Function, 9*(1), 407–416. https://doi.org/10.1039/c7fo01568b.

Ohno, M., Togashi, Y., Tsuda, K., Okawa, K., Kamaya, M., Sakaguchi, M., … Oyama, F. (2013). Quantification of chitinase mRNA levels in human and mouse tissues by real-time PCR : Species-specific expression of acidic mammalian chitinase in stomach tissues. *PLoS ONE, 8*(6), Article e67399. https://doi.org/10.1371/journal.pone.0067399.

Oliveira, L. de L. de, Carvalho, M. V. de, & Melo, L. (2014). Health promoting and sensory properties of phenolic compounds in food. Revista Ceres, 61, 764–779.

Omotoso, O. T. (2015). An evaluation of the nutrients and some anti-nutrients in silkworm, *Bombyx mori* L. (Bombycidae: Lepidoptera). *Jordan. Journal of Biological Sciences, 8*(1), 45–50.

Oonincx, D. G. A. B., van Broekhoven, S., van Huis, A., & van Loon, J. J. A. (2015). Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS ONE, 10*(12), 1–20. https://doi.org/10.1371/journal.pone.0144601.

Oranut, S., Subhachai, B., Shen, L. R., & Li, D. (2010). Lipids and fatty acid composition of dried edible red and black ants. *Agricultural Sciences in China, 9*(7), 1072–1077. https://doi.org/10.1016/S1671-2927(09)60192-9.

Paoletti, M. G., Norberto, L., Damini, R., & Musumeci, S. (2007). Human gastric juice contains chitinase that can degrade chitin. *Annals of Nutrition and Metabolism, 51*, 244–251. https://doi.org/10.1159/000104144.

Paul, D., & Dey, S. (2014). Essential amino acids, lipid profile and fat-soluble vitamins of the edible silkworm *Bombyx mori* (Lepidoptera: Bombycidae). *International Journal of Tropical Insect Science, 34*(4), 239–247. https://doi.org/10.1017/S1742758414000526.

Peñaflorida, V. D. (1989). An evaluation of indigenous protein sources as potential component in the diet formulation for tiger prawn, *Penaeus monodon*, using essential

amino acid index (EAAI). *Aquaculture, 83*, 319–330. https://doi.org/10.1016/0044-8486(89)90043-4.
Pérez-Santín, E., Calvo, M. M., López-Caballero, M. E., Montero, P., & Gómez-Guillén, M. C. (2013). Compositional properties and bioactive potential of waste material from shrimp cooking juice. *LWT – Food Science and Technology, 54*, 87–94. https://doi.org/10.1016/j.lwt.2013.05.038.
Pettit, G. R., Meng, Y., Herald, D. L., Knight, J. C., & Day, J. F. (2005). Antineoplastic agents. 553. The Texas grasshopper *Brachystola magna*. *Journal of Natural Products, 68*, 1256–1258. https://doi.org/10.1021/np0402367.
Pires, D. R., de Morais, A. C. N., Coelho, C. C. S., Marinho, A. F., Góes, L. C. D. S. A., Augusta, I. M., … Saldanha, T. (2018). Nutritional composition, fatty acids and cholesterol levels in Atlantic white shrimp (*Litopenaeus schimitti*). *International Food Research Journal, 25*(1), 151–157.
Prapasuwannakul, N., & Suwannahong, K. (2015). Chemical composition and antioxidant activity of Klongkone shrimp paste. *Procedia - Social and Behavioral Sciences, 197*, 1095–1100. https://doi.org/10.1016/j.sbspro.2015.07.351.
Prosky, L. (2000). When is dietary fiber considered a functional food? *BioFactors, 12*, 289–297.
Randriamahatody, Z., Sylla, K. S. B., Nguyen, H. T. M., Donnay-Moreno, C., Razanamparany, L., Bourgougnon, N., & Bergé, J. P. (2011). Proteolysis of shrimp by-products (*Peaneus monodon*) from Madagascar. *CyTA - Journal of Food, 9*(3), 220–228. https://doi.org/10.1080/19476337.2010.518250.
Rincón-León, F. (2003). Functional foods. *Encyclopedia of Food Sciences and Nutrition*, 2827–2832. https://doi.org/10.1016/B0-12-227055-X/01328-6.
Rubel, H., Woods, W., Pérez, D., Unnikrishnan, S., Felde, A. M. Zum, Zielcke, S., … Lanfer, C. (2019). A strategic approach to sustainable shrimp production in Thailand: The case for improved economics and sustainability.
Ruethers, T., Taki, A. C., Johnston, E. B., Nugraha, R., Le, T. T. K., Kalic, T., … Lopata, A. L. (2018). Seafood allergy: A comprehensive review of fish and shellfish allergens. *Molecular Immunology, 100*, 28–57. https://doi.org/10.1016/j.molimm.2018.04.008.
Rumpold, B. A., & Schlüter, O. K. (2013). Nutritional composition and safety aspects of edible insects. *Molecular Nutrition & Food Research, 57*, 802–823. https://doi.org/10.1002/mnfr.201200735.
Sabolová, M., Adámková, A., Kouřimská, L., Chrpová, D., & Pánek, J. (2016). Minor lipophilic compounds in edible insects. *Potravinarstvo, 10*(1), 400–406. https://doi.org/10.5219/605.
Sachindra, N. M., Bhaskar, N., & Mahendrakar, N. S. (2005). Carotenoids in different body components of Indian shrimps. *Journal of the Science of Food and Agriculture, 85*(1), 167–172. https://doi.org/10.1002/jsfa.1977.
Salah, R., Michaud, P., Mati, F., Harrat, Z., Lounici, H., Abdi, N., … Mameri, N. (2013). Anticancer activity of chemically prepared shrimp low molecular weight chitin evaluation with the human monocyte leukaemia cell line, THP-1. *International Journal of Biological Macromolecules, 52*, 333–339. https://doi.org/10.1016/j.ijbiomac.2012.10.009.
Schmidt, A., Call, L. M., Macheiner, L., & Mayer, H. K. (2019). Determination of vitamin B12 in four edible insect species by immunoaffinity and ultra-high performance liquid chromatography. *Food Chemistry, 281*, 124–129. https://doi.org/10.1016/j.foodchem.2018.12.039.
Seo, M., Goo, T.-W., Chung, M. Y., Baek, M., Hwang, J. S., Kim, M.-A., & Yun, E.-Y. (2017). *Tenebrio molitor* larvae inhibit adipogenesis through AMPK and MAPKs signaling in 3T3-L1 adipocytes and obesity in high-fat diet-induced obese mice. *International Journal of Molecular Sciences, 18*. https://doi.org/10.3390/ijms18030518.
Seo, M., Kim, J., Moon, S.-S., Hwang, J.-S., & Kim, M.-A. (2017). Intraventricular administration of *Tenebrio molitor* larvae extract regulates food intake and body weight in mice with high-fat diet-induced obesity. *Nutrition Research, 44*, 18–26. https://doi.org/10.1016/j.nutres.2017.05.011.
Seymour, T. A., Li, S. J., & Morrissey, M. T. (1996). Characterization of a natural antioxidant from shrimp shell waste. *Journal of Agricultural and Food Chemistry, 44*, 682–685. https://doi.org/10.1021/jf950597f.
Shahidi, F., Arachchi, J. K. V., & Jeon, Y. J. (1999). Food applications of chitin and chitosans. *Trends in Food Science and Technology, 10*, 37–51. https://doi.org/10.1016/S0924-2244(99)00017-5.
Shamim, G., Ranjan, S. K., Pandey, D. M., & Ramani, R. (2014). Biochemistry and biosynthesis of insect pigments. *European Journal of Entomology, 111*(2), 149–164. https://doi.org/10.14411/eje.2014.021.
Slocinska, M., Marciniak, P., & Rosinski, G. (2008). Insects antiviral and anticancer peptides: New leads for the future? *Protein & Peptide Letters, 15*(6), 578–585. https://doi.org/10.2174/092986608784966912.
Smetana, S., Leonhardt, L., Kauppi, S.-M., Pajic, A., & Heinz, V. (2020). Insect margarine: Processing, sustainability and design. *Journal of Cleaner Production, 264*, Article 121670. https://doi.org/10.1016/j.jclepro.2020.121670.
Song, C., Yu, H., Zhang, M., Yang, Y., & Zhang, G. (2013). Physicochemical properties and antioxidant activity of chitosan from the blowfly *Chrysomya megacephala* larvae. *International Journal of Biological Macromolecules, 60*, 347–354. https://doi.org/10.1016/j.ijbiomac.2013.05.039.
Sowmya, R., & Sachindra, N. M. (2012). Evaluation of antioxidant activity of carotenoid extract from shrimp processing byproducts by in vitro assays and in membrane model system. *Food Chemistry, 134*, 308–314. https://doi.org/10.1016/j.foodchem.2012.02.147.
Sriket, P., Benjakul, S., Visessanguan, W., & Kijroongrojana, K. (2007). Comparative studies on chemical composition and thermal properties of black tiger shrimp (*Penaeus monodon*) and white shrimp (*Penaeus vannamei*) meats. *Food Chemistry, 103*, 1199–1207. https://doi.org/10.1016/j.foodchem.2006.10.039.
Srinivasan, H., Velayutham, K., & Ravichandran, R. (2018). Chitin and chitosan preparation from shrimp shells *Penaeus monodon* and its human ovarian cancer cell line, PA-1. *International Journal of Biological Macromolecules, 107*, 662–667. https://doi.org/10.1016/j.ijbiomac.2017.09.035.
Stull, V. J., Finer, E., Bergmans, R. S., Febvre, H. P., Longhurst, C., Manter, D. K., … Weir, T. L. (2018). Impact of edible cricket consumption on gut microbiota in healthy adults, a double-blind, randomized crossover trial. *Scientific Reports, 8*, 1–13. https://doi.org/10.1038/s41598-018-29032-2.
Tamang, J. P., Shin, D.-H., Jung, S.-J., & Chae, S.-W. (2016). Functional properties of microorganisms in fermented foods. *Frontiers in Microbiology, 7*(578), 1–13. https://doi.org/10.3389/fmicb.2016.00578.
Tanaka, K., Sakai, T., Ikeda, I., Imaizumi, K., & Sugano, M. (1998). Effects of dietary shrimp, squid and octopus on serum and liver lipid levels in mice. *Bioscience, Biotechnology and Biochemistry, 62*(7), 1369–1375.
Turan, H., Kaya, Y., & Erdem, M. E. (2011). Proximate composition, cholesterol, and fatty acid content of brown shrimp (*Crangon crangon* L. 1758) from Sinop region, Black Sea. *Journal of Aquatic Food Product Technology, 20*, 100–107. https://doi.org/10.1080/10498850.2010.526753.
Tzompa-Sosa, D. A., Yi, L., van Valenberg, H. J. F., van Boekel, M. A. J. S., & Lakemond, C. M. M. (2014). Insect lipid profile: Aqueous versus organic solvent-based extraction methods. *Food Research International, 62*, 1087–1094. https://doi.org/10.1016/j.foodres.2014.05.052.
Tzompa-Sosa, D. A., & Fogliano, V. (2017). Potential of insect-derived ingredients for food applications. In Insect Physiology and Ecology. IntechOpen. https://doi.org/10.5772/67318.
Usui, M., Harada, A., Yasumoto, S., Sugiura, Y., Nishidai, A., Ikarashi, M., … Kondo, M. (2015). Relationship between the risk for a shrimp allergy and freshness or cooking. *Bioscience, Biotechnology and Biochemistry, 79*(10), 1698–1701. https://doi.org/10.1080/09168451.2015.1045830.
van Huis, A. (2003). Insects as food in sub-saharan africa. *Insect Science and Its Application, 23*(3), 163–185.
van Huis, A., & Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development, 37*(43), 14. https://doi.org/10.1007/s13593-017-0452-8.
van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects: Future prospects for food and feed security*. Rome: FAO.
Vattem, D. A., & Maitin, V. (2016). Functional foods, nutraceuticals and natural products: concepts and applications.
Vercruysse, L., Smagghe, G., Herregods, G., & Van Camp, J. (2005). ACE inhibitory activity in enzymatic hydrolysates of insect protein. *Journal of Agricultural and Food Chemistry, 53*(13), 5207–5211. https://doi.org/10.1021/jf050337q.
Vercruysse, L., Smagghe, G., Matsui, T., & Van Camp, J. (2008). Purification and identification of an angiotensin I converting enzyme (ACE) inhibitory peptide from the gastrointestinal hydrolysate of the cotton leafworm, Spodoptera littoralis. *Process Biochemistry, 43*, 900–904. https://doi.org/10.1016/J.PROCBIO.2008.04.014.
Vieira, M. A., Oliveira, D. D., & Kurozawa, L. E. (2016). Production of peptides with radical scavenging activity and recovery of total carotenoids using enzymatic protein hydrolysis of shrimp waste. *Journal of Food Biochemistry, 40*(4), 517–525. https://doi.org/10.1111/jfbc.12246.
Wang, W., Shen, S., Chen, Q., Tanga, B., He, G., Ruan, H., & Das, U. N. (2008). Hydrolyzates of silkworm pupae (*Bombyx mori*) protein is a new source of angiotensin I-converting enzyme inhibitory peptides (ACEIP). *Current Pharmaceutical Biotechnology, 9*, 307–314. https://doi.org/10.2174/138920108785161578.
Wang, Y.-K., He, H.-L., Chen, X.-L., Sun, C.-Y., Zhang, Y.-Z., & Zhou, B.-C. (2008). Production of novel angiotensin I-converting enzyme inhibitory peptides by fermentation of marine shrimp *Acetes chinensis* with *Lactobacillus fermentum* SM 605. *Applied Microbiology and Biotechnology, 79*, 785–791. https://doi.org/10.1007/s00253-008-1489-z.
Wang, Y., Sha, Y., Nair, S., Gagnon, J., Srinivasan, P., Albert, D., … Hanna, P. (2016). Shrimp protein improves oral glucose tolerance in high-fat diet-induced obese mice. *BAOJ Nutrition, 2*(3), 1–7. https://doi.org/10.24947/baojn/2/3/00120.
WHO/FAO/UNU (2007). Protein and amino acid requirements in human nutrition: report of a joint FAO/WHO/UNU expert consultation.
Williams, J. P., Williams, J. R., Kirabo, A., Chester, D., & Peterson, M. (2016). Nutrient content and health benefits of insects. In *Insects as sustainable food ingredients* (pp. 61–84). Elsevier Inc.. https://doi.org/10.1016/B978-0-12-802856-8.00003-X
Wu, Q., Jia, J., Tan, G., Xu, J., & Gui, Z. (2011). Physicochemical properties of silkworm larvae protein isolate and gastrointestinal hydrolysate bioactivities. *African Journal of Biotechnology, 10*(32), 6145–6153. https://doi.org/10.5897/AJB10.1864.
Xia, Z., Chen, J., & Wu, S. (2013). Hypolipidemic activity of the chitooligosaccharides from *Clanis bilineata* (Lepidoptera), an edible insect. *International Journal of Biological Macromolecules, 59*, 96–98. https://doi.org/10.1016/j.ijbiomac.2013.04.017.
Yanar, Y., & Çelik, M. (2006). Seasonal amino acid profiles and mineral contents of green tiger shrimp (*Penaeus semisulcatus* de Haan, 1844) and speckled shrimp (*Metapenaeus monoceros* Fabricus, 1789) from the Eastern Mediterranean. *Food Chemistry, 94*(1), 33–36. https://doi.org/10.1016/j.foodchem.2004.09.049.
Yerlikaya, P., Topuz, O. K., Buyukbenli, H. A., & Gokoglu, N. (2013). Fatty acid profiles of different shrimp species: Effects of depth of catching. *Journal of Aquatic Food Product Technology, 22*, 290–297. https://doi.org/10.1080/10498850.2011.646388.

Yoon, Y. I., Chung, M. Y., Hwang, J.-S., Han, M. S., Goo, T.-W., & Yun, E.-Y. (2015). *Allomyrina dichotoma* (Arthropoda: Insecta) larvae confer resistance to obesity in mice fed a high-fat diet. *Nutrients, 7*, 1978–1991. https://doi.org/10.3390/nu7031978.

Zamudio-Flores, P. B., Tirado-Gallegos, J. M., Espino-Díaz, M., Ochoa-Reyes, E., Hernández-Centeno, F., Hernández-Gonzaléz, M., … Sánchez-Ortíz, O. (2019). Food supplements from a grasshopper: A developmental stage-wise evaluation of amino acid profile, protein and vitamins in *Brachystola magna* (Girard). *Emirates Journal of Food and Agriculture, 31*(7), 561–568. https://doi.org/10.9755/EJFA.2019.V31.I7.1989.

Zhang, H., Wang, P., Zhang, A.-J., Li, X., Zhang, J.-H., Qin, Q.-L., & Wu, Y.-J. (2016). Antioxidant activities of protein hydrolysates obtained from the housefly larvae. *Acta Biologica Hungarica, 67*(3), 236–246. https://doi.org/10.1556/018.67.2016.3.2.

Zhenxing, L., Caolimin, L., & Jamil, K. (2006). Reduction of allergenic properties of shrimp (*Penaeus vannamei*) allergens by high intensity ultrasound. *European Food Research and Technology, 223*, 639–644. https://doi.org/10.1007/s00217-005-0246-0.

Zielińska, E., Baraniak, B., & Karaś, M. (2017). Antioxidant and anti-inflammatory activities of hydrolysates and peptide fractions obtained by enzymatic hydrolysis of selected heat-treated edible insects. *Nutrients, 9*, 1–14. https://doi.org/10.3390/nu9090970.

Zielińska, E., Baraniak, B., Karaś, M., Rybczyńska, K., & Jakubczyk, A. (2015). Selected species of edible insects as a source of nutrient composition. *Food Research International, 77*, 460–466. https://doi.org/10.1016/j.foodres.2015.09.008.

Zielińska, E., Karaś, M., & Jakubczyk, A. (2017). Antioxidant activity of predigested protein obtained from a range of farmed edible insects. *International Journal of Food Science and Technology, 52*(2), 306–312. https://doi.org/10.1111/ijfs.13282.