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REVIEW

Potential health benefits of edible insects

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ABSTRACT
Animal-based foods have traditionally been viewed as dietary staples because they provide many essential nutrients; however, edible insects have the potential to serve as healthy, sustainable alternatives to these because of their nutrient contents. Edible insects may have superior health benefits due to their high levels of vitamin B_{12}, iron, zinc, fiber, essential amino acids, omega-3 and omega-6 fatty acids, and antioxidants. The addition of edible insects such as crickets to the human diet could offer a myriad of environmental and nutritional benefits including an overall reduction in greenhouse gas emissions, decreased agricultural use of land and water, improved prevention and management of chronic diseases like diabetes, cancer, and cardiovascular disease, and enhanced immune function. Future research should aim to understand the beneficial effects of whole insects or insect isolates in comparison to traditional animal- and plant-based foodstuffs. Ultimately, insects have the potential to be used as meat substitutes or dietary supplements, resulting in human health and environmental benefits. The purpose of this review is to provide additional insight on the nutrient composition of edible insects, their potential use as meat substitutes or dietary supplements, the associated health and wellness benefits, and their potential role in exercise performance.

KEYWORDS
Health benefits; edible insects; cricket; sustainable agriculture; protein alternatives; physical exercise

Introduction

Insects have traditionally been consumed as a food source by nearly 2 billion people around the world, making up part of many countries' diets (Halloran et al. 2014; Van Huis et al. 2013). Most insects contain many of the nutrients that are essential to the human diet, including fats, proteins, fiber, vitamins, and minerals (Halloran et al. 2014; Van Huis et al. 2013; Raheem et al. 2019). In fact, the nutrient composition of many edible insects is comparable to that of other traditionally consumed animal and plant foods (Halloran et al. 2014; Raheem et al. 2019). According to Halloran et al., most edible insects meet the daily energy and nutrient requirements, containing polyunsaturated and monounsaturated fatty acids, essential amino acids, zinc, iron, and fiber (Halloran et al. 2014). They may also act as an alternative protein source to other animal protein sources like chicken, beef, and fish (Halloran et al. 2014). A recent review by Raheem et al. further explains that most insects, especially crickets, meet or exceed the recommended amounts of most of the essential amino acids for adults, including histidine, isoleucine, leucine, lysine, threonine, tryptophan, and valine (Raheem et al. 2019). Raheem et al. also notes that edible insects are rich in protein and contain higher quantities of protein than soybean, a traditional plant protein source. Additionally, chitin, which is found in the exoskeletons of many different insects, is a good source of fiber and may enhance the immune system (Raheem et al. 2019). Many insects are also good sources of micronutrients including B vitamins, zinc, and iron (Raheem et al. 2019). Insects may be processed into various forms such as pastes, powders, and meals, which increases their shelf-lives and allows them to easily be used as substitutes in cooking and baking with little change to the taste, texture, or appearance of a dish (Dossey, Tatum, and McGill 2016). Nutrients such as vitamins, minerals, fats, and proteins may also be isolated from insects, allowing for the potential use of insects as dietary supplements (Van Huis et al. 2013).

In addition to their nutritional importance in diets worldwide, insects have the potential to act as a more environmentally friendly and sustainable nutrient source in human diets than other widely consumed animal nutrient sources (Halloran et al. 2014). Insects are much more efficient at feed conversion (converting their feed into edible food) than other animals, such as chickens, cattle, and pigs (Oonincx et al. 2015). Unlike other animal food sources that require plant-based feeds like grains, insects may be grown from organic waste streams from humans and animals, making them more sustainable and inexpensive to raise (Halloran et al. 2014; Van Huis et al. 2013; Raheem et al. 2019). By consuming more insect-based foods rather than animals, the grains that are used to feed animal food sources could even be used to feed people, which is of concern with the growing world population (Halloran et al. 2014).

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Further, raising insects requires little land and water and produces less greenhouse gases than raising pigs and cattle (Oonincx et al. 2010). According to Mason et al., the water requirements per gram of protein of cricket are only 0.7–0.8 g, while the water requirements per gram of protein of cattle is approximately 16.8 g. The methane and carbon dioxide emissions per kilogram of cricket produced are also significantly lower than those for cattle, at 0.7 g for crickets compared to 114 g for cattle and 7.6 g for crickets compared to 285 g for cattle, respectively (Mason et al. 2018).

Overall, there are many positive nutritional and environmental implications for the use of insects as a food source. Insects may even be a more affordable source of high-quality protein and micronutrients, potentially addressing global protein and micronutrient deficiencies (Van Huis et al. 2013). Further, potential health benefits of edible insects, such as their ability to enhance immune function, may imply that edible insects could be used as dietary supplements and substitutes in human diets to improve health and wellness. As the topic of sustainable food sources becomes increasingly important due to the environmental footprint of animal and plant proteins, alternate food sources that may provide similar nutrition and act as substitutes for animal foods need to be explored. There is currently a gap in the literature surrounding house crickets and other edible insects as protein alternatives in human diets. The purpose of this review is to provide additional insight on the nutrient composition of edible insects, their potential use as meat substitutes or dietary supplements, the associated health and wellness benefits, and their potential role in exercise performance. Despite the environmental and economic benefits of insect-based foods, so far, only a small number of researches investigated their potential health-promoting effects for the purpose of either human consumption or animal feed. Various other reviews have investigated the nutritional composition of edible insects, compiling information on their nutrient diversity (Kinyuru et al. 2015; Belluco et al. 2013; Churchward-Venne et al. 2017; Mwangi et al. 2018), thus we have chosen to focus our discussion mainly on the potential health benefits provided by the human and animal consumption of insect-based food. In this context, we did not seek to separate our discussion to human and animal wellness nor disease categories, instead, we aimed to elaborate on the mechanisms of action underlying whole insects or insect isolates in different experimental settings and their potential implications as foodstuffs or dietary supplements. Our discussion is a narrative review of the current literature. Recent studies that included relevant information about the nutritional composition and potential health benefits of edible insects in animal studies and human trials were selected for inclusion in this review.

Nutrient composition

Edible insects contain relatively high quantities of nutrients that are essential to the human diet and it is estimated that, depending on the species, approximately 77–98% of insects are digestible (Dobermann, Swift, and Field 2017). Some edible insects, like the house cricket (*Acheta domesticus*), have been found to be significantly more nutritious than traditional foods like beef and chicken based on the amounts of carbohydrate, energy, saturated fat, and sodium that they provide (Payne et al. 2016). Many of these edible insects are protein-rich and are estimated to contain approximately 7–48% of protein by dry weight (Kinyuru et al. 2015; Churchward-Venne et al. 2017; Dobermann, Swift, and Field 2017). For example, the house cricket has an average protein content of approximately 65% of dry matter, which is superior to other animal and plant sources such as beef, eggs, milk, and soybeans where protein makes up approximately 50, 52, 30, and 45% of dry matter, respectively (Churchward-Venne et al. 2017; Rumpold and Schlüter 2015). It is recommended that humans diets have an essential amino acid score of at least 40% and the scores of most edible insects typically range from 46% to 96% (Kinyuru et al. 2015). For example, not only does the house cricket meet the essential amino acid requirements imposed by the World Health Organization (WHO), but it contains even greater quantities of some types of essential amino acid than animal and plant protein sources like beef, eggs, and soybeans (Churchward-Venne et al. 2017; Rumpold and Schlüter 2015; von Hackewitz 2018). Specifically, the leucine content of insects falling within the Orthoptera group, including the house cricket, is greater than the leucine content found in soy protein by approximately 13 mg/g and is comparable to the quantity found in animal sources such as skim milk (Churchward-Venne et al. 2017). Lysine is another essential amino acid that can be low in plant protein sources that tends to be found in larger quantities in edible insects (Kinyuru et al. 2015). The house cricket meets most of the essential amino acid requirements, nonetheless, it may not be as good of a source of methionine, serine, and tryptophan as other animal sources like beef and eggs (von Hackewitz 2018). While the house cricket appears to be an excellent source of high-quality protein, it is important to note that the protein and amino acid content of the house cricket, as well as other edible insects, is dependent upon environmental factors, including the life stage of the insects, their food, and their sex (Kinyuru et al. 2015; Dobermann, Swift, and Field 2017; von Hackewitz 2018).

Most edible insects tend to be high in unsaturated fats, especially polyunsaturated fatty acids (PUFAs) (Kinyuru et al. 2015; Dobermann, Swift, and Field 2017; Rumpold and Schlüter 2015). These include linolenic and linoleic acids, commonly referred to as omega-3 and omega-6 fatty acids, respectively. PUFAs are heart-healthy fats that tend to be found most commonly in plant oils, nuts, seeds and fish; however, edible insects do not contain eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA), which are typically found in fish (Kinyuru et al. 2015; Dobermann, Swift, and Field 2017). When compared with their saturated fatty acid content, edible insects contain more PUFAs, which suggests that edible insect species likely have a lower cholesterol content (Kinyuru et al. 2015). Specifically, insects in the Orthoptera group, including the house cricket, only contain fat in about 13.4% of their dry matter (Rumpold and

Schlüter 2015). The saturated fat content of the house cricket is similar to that of other meats, but the total fat content of the house cricket is lower than the total fat of chicken, beef, and pork (Payne et al. 2016; Voelker 2019). Like most edible insects, insects in the Orthoptera group have a high PUFA content, however, as with essential amino acid content, the essential fatty acid and cholesterol levels of insects are contingent upon environmental factors such as sex, feed, and life stage (Rumpold and Schlüter 2015).

In addition to their high protein and unsaturated fat content, edible insects are rich in several vitamins and minerals. Most insects, especially crickets, are rich in iron, with iron levels ~3-fold higher than those of beef (Payne et al. 2016; Voelker 2019). The iron content that is present in edible insects is heme-iron and is easier for humans to digest than the form of iron that is commonly found in plants (Dobermann, Swift, and Field 2017). Specifically, the house cricket is composed of approximately 8.75 mg of iron per 100 grams of dry matter and it is estimated that crickets have a 180% greater iron content than beef, making them a comparable, if not better source of iron than traditional animal sources (Mwangi et al. 2018; Payne et al. 2016). The house cricket is also rich in vitamin B_{12}, containing approximately 5.4 mg of vitamin B_{12} per 100 grams of dry matter (Mason et al. 2018; Kinyuru et al. 2015). Another study by Schmidt et al., found that crickets contain approximately 2.88 μg/100 g of dry matter of vitamin B_{12}, which falls within the recommended range for adults (Schmidt et al. 2019). According to reports by Voelker and Mason et al, the nutritional analysis of cricket powders has shown that crickets contain about 10 times more vitamin B_{12} than beef (Mason et al. 2018; Voelker 2019). The house cricket also contains high quantities of other B vitamins such as thiamin, riboflavin, and folic acid, making them an excellent source of B vitamins (Kinyuru et al. 2015; Payne et al. 2016; Rumpold and Schlüter 2015; von Hackewitz 2018). Additionally, the house cricket is a good source of calcium, zinc, sodium, vitamin A, and vitamin C (Dobermann, Swift, and Field 2017; Payne et al. 2016; von Hackewitz 2018). When compared to meats like chicken, pork, and beef, crickets contain greater quantities of calcium, sodium, iron, riboflavin, vitamin A, and vitamin C (Payne et al. 2016; Voelker 2019). Montowska et al. assessed the mineral content of three edible cricket powders from different commercial suppliers and found that 100 grams of cricket powders provided 14–22% of RDA for calcium, which is comparable to tofu, salmon, cottage cheese, and fortified orange juice (Montowska et al. 2019). Crickets and other edible insects contain comparable or even greater quantities of iron and zinc to traditional animal sources, falling within the recommended range for adults (Mwangi et al. 2018; Montowska et al. 2019). Also, Latunde-Dada et al. reported that grasshopper, cricket and mealworms consisted of much higher chemically available calcium, copper, zinc, magnesium and manganese than sirloin beef, while the bioavailability of iron, calcium and manganese of cricket and sirloin beef was comparably higher than that of grasshopper, meal, and buffalo worms (Latunde-Dada, Yang, and Vera Aviles 2016). Finally, chitin, a substance that is found in the hard exoskeleton of the house cricket, is indigestible and serves as a good source of dietary fiber (Kinyuru et al. 2015). According to Voelker, approximately 8.5% of the weight of cricket powder is composed of dietary fiber, likely originating from their chitinous exoskeleton (Voelker 2019).

Health benefits

This section provides a summary of health benefits and the underlying mechanisms of action of edible insects in different experimental settings, as well as their potential implications as foodstuffs or dietary supplements. Table 1 summarizes representative studies on possible health benefits of whole insects or insect isolates in animals or human trials.

Gastrointestinal health

Several components of edible insects have the potential to benefit human health, such as chitin, short-chain fatty acids, medium-chain fatty acids, and glycosaminoglycans. In a study by Stull et al. supplementing with 25 grams/day dried, roasted cricket powder for 14 days in healthy adults, increased probiotic bacterium *Bifidobacterium animalis* and decreased plasma tumor necrosis factor (TNF)-α (Stull et al. 2018). The relative abundance of *Bifidobacterium animalis*, a probiotic associated with the prevention of respiratory infections, diarrhea, and antibiotic side effects, was found elevated after intervention, suggesting that the cricket supplement produced microbiota with the potential to improve gastrointestinal health (Stull et al. 2018). TNF-α is a critical pro-inflammatory cytokine, which has been found to contribute to the pathological processes of various diseases, such as rheumatoid arthritis, inflammatory bowel diseases, multiple sclerosis, and multiple types of cancer (Chu 2013). Thus, Stull's findings suggest that cricket may exert a protective effect on inflammatory processes. An enhanced microbial diversity has also been seen in rainbow trout that were fed black soldier fly (*Hermetia illucens*) larvae and the increasing biodiversity of microbes in the gut promoted resilience, as they competed with pathogens for nutrients and colonization sites (Bruni et al. 2018). The antimicrobial effect of dry mealworm (*Tenebrio molitor*) and super mealworm (*Zophobas morio*) has been assessed. It is found that 0.4% dry mealworm and super mealworm larvae probiotics effectively helped to reduce the infection of *E. coli* and *Salmonella* in broiler chickens (Islam and Yang 2017). These beneficial effects of insects on gut microbiome and the antimicrobial effect have been associated with their chitin content. Chitin, a polymer of β-1, 4N-acetylglucosamine, is the primary components of the insect exoskeleton (Stull et al. 2018; Borrelli et al. 2017). For example, the dietary fiber content of cricket powder is roughly equivalent to that found in whole wheat and soy powder in quantity, and its fiber is entirely composed of chitin (*unpublished*, analysis performed by Maxxam Analytics, Mississauga, Canada). Chitin and its degraded products such as chitosan have been shown to exert antimicrobial, antioxidant, anti-inflammatory, anticancer and immunostimulatory activity (Liaqat and Eltem 2018).

In relation to increasing the abundance and diversity of beneficial bacteria within the gut, insect-based diet is associated with the production of short-chain fatty acids (SCFAs). In a study on chickens, it was found that SCFA propionate and butyrate are produced when chitin is broken down by microbiota in the gut (Borrelli et al. 2017). These SCFAs cause the release of hormones associated with satiety, so the chickens receiving the insect diet consumed less food than those receiving a soybean diet (Borrelli et al. 2017). The increased amounts of propionate and butyrate were associated with lowered blood cholesterol and triglyceride levels in the chickens receiving the insect meal diet as well as an increase in energy (Borrelli et al. 2017). Oral intake of chitooligosaccharides, the depolymerized product of chitin and chitosan, for 8 weeks significantly reduced the level of pro-inflammatory cytokine TNF-α and interleukin (IL)-1β in the elderly (Kim et al. 2006). A study by Harikrishnan et al. on chitin and chitosan supplementation in fish showed increased white blood cells, hemoglobin, and red blood cells in fish that received a chitin or chitosan supplement in their diet, thus improving the immune function of the fish (Harikrishnan et al. 2012). Another study on chickens has shown that meal supplementing with black soldier fly larvae lowered triglyceride and cholesterol levels and elevated blood calcium levels. A possible mechanism is because of the positive charge of chitin, which allows it to bind to free fatty acids and bile acids that are negatively charged (Marono et al. 2017). Taken together, increases in probiotics and SCFA production and decreases in pro-inflammatory cytokines and plasma lipids caused by insect consumption—possibly due to the chitin content— may help to improve immune response and function in humans, especially in the gastrointestinal tract.

Antioxidant and anti-inflammatory properties

Glycosaminoglycan, a polysaccharide found in crickets, has been investigated in various rodent models by Ahn et al. (Ahn et al. 2014; Ahn et al. 2016; Ahn et al. 2019). They found that glycosaminoglycan derived from *Gryllus bimaculatus* (a type of cricket) produced a significant anti-inflammatory effect against chronic arthritis in rats by inhibiting C-reactive protein (CRP) and rheumatoid factor, and suppressed a number of inflammatory biomarkers in vitro (Ahn et al. 2014). Additionally, the combination of indomethacin (a non-steroidal anti-inflammatory drug) and glycosaminoglycan was more efficacious than either agent alone in suppressing paw edema (Ahn et al. 2014). In high-fat diet-fed rats, cricket derived glycosaminoglycan reduced CRP levels, abdominal and epididymidal fat mass, and various sero-biochemical parameters (phospholipid, aspartate transaminase (AST), alanine transaminase (ALT), total cholesterol and glucose), suggesting the potential use of glycosaminoglycan in preventing fatty liver or hyperlipidemia (Ahn et al. 2016). Another study involving glycosaminoglycan supplementation in diabetic mice found that diabetic mice receiving the glycosaminoglycan treatment exhibited a reduction in blood glucose and LDL-cholesterol levels and an increase in the activity of antioxidant enzymes (catalase, superoxide dismutase and glutathione peroxidase) (Ahn et al. 2019). These results indicate that the glycosaminoglycan found in crickets may aid in lowering the risk of developing diabetes and chronic inflammatory diseases.

Many insect-based foodstuffs, including cricket powder, contain high quantities of bioactive peptides with antioxidant and antimicrobial properties. The biological effects of proteins from edible insects after enzymatic hydrolysis has been reviewed by Nongonierma et al (Nongonierma and FitzGerald 2017). For instance, these antimicrobial peptides benefited and improved the gastrointestinal health of chickens and pigs, while also helping to increase their immune function and improve their ability to digest nutrients from their feed (Gasco, Finke, and Van Huis 2018). Another study by Zielinska et al. on the anti-inflammatory properties of heat-treated insects showed that treating insects with heat increases the amount of bioactive peptides produced (Zielińska, Baraniak, and Karaś 2017). The antioxidant properties of insect hydrolysates and peptide fractions may aid in reducing inflammation and oxidative stress by lowering the amount of free radicals present in the body (Zielińska, Baraniak, and Karaś 2017; Messina et al. 2019). It has been found that water-soluble extracts of grasshoppers, silkworm, and crickets have an antioxidant capacity that is approximately 5 times greater than the antioxidant capacity of fresh orange juice in vitro, which is likely attributed to their higher protein/peptide content (Di Mattia et al. 2019). Enzymatic hydrolysis also may reduce the allergenicity of bioactive properties extracted from cricket (*Gryllodes sigillatus*) (Hall, Johnson, and Liceaga 2018). Taken together, insect powders and their peptide hydrolysates may potentially prevent the incidence of cancer, cardiovascular disease, and diabetes, which have been associated with oxidative stress and chronic inflammation.

Other health benefits

Other nutritional components that are common in insects, including the medium-chain fatty acid lauric acid, globulin and albumin proteins, have had positive effects on the health of mice and pigs. The unsaturated fatty acid content of insects including mealworms, crickets, and housefly maggots may help to reduce the risk of developing cardiovascular disease (Makkar et al. 2014). A study by Sprangers et al. discusses the antimicrobial effects of lauric acid found in black soldier flies on piglets (Spranghers et al. 2018). Lauric acid from the flies helped to prevent bacterial infections and control gram-positive bacterial infections in the guts of piglets and had an even stronger antimicrobial effect when the black soldier fly supplement was combined with lipase in the piglet feed (Spranghers et al. 2018). Several studies on broiler chickens and early-weaned piglets have observed increased globulin and/or decreased albumin protein levels that were fed insect meals as a replacement of soybean meal (Marono et al. 2017; Bovera et al. 2015; Ji et al. 2016). A decreased rate of diarrhea was also found in early-weaned piglets without affecting growth performance (Ji et al. 2016). These effects have been associated with increased disease resistance and immune response in animals, which may indicate a potential increase in these in humans as well. Additionally, the rich vitamin and mineral content of edible insects pose implications for their potential health benefits. The vitamin B_{12} content of crickets could aid in the prevention of pernicious anemia, cognitive decline, and bone fractures in elderly individuals, and may also reduce the risk of cardiovascular disease through the reduction of total homocysteine concentrations, a protein found in blood plasma that has been associated with the development of cardiovascular disease (Makkar et al. 2014; Spranghers et al. 2018). The inclusion of crickets in the human diet may also improve bone mineral density and decrease the incidence of bone fracture, particularly in older adults, due to their rich calcium content (Ji et al. 2016). Further, if edible insects are incorporated into the human diet, the iron and zinc contents of crickets and other edible insects have the potential to prevent anemia and improve immune function, cognitive function, and gastrointestinal health in humans (Koopman et al. 2007).

Potential use as a supplement for exercise

Based on their nutrient composition, insect powders could be used as a dietary protein supplement to resistance exercise in order to build muscle mass by increasing muscle protein synthesis. Muscle protein synthesis is stimulated by amino acid availability. Following resistance exercise, muscle protein synthesis has been shown to be enhanced for 48 h. The consumption of dietary supplements containing both carbohydrate and protein after resistance exercise have been shown to increase protein synthesis and insulin production (Koopman et al. 2005). Carbohydrate consumption following resistance exercise increases insulin levels, which helps to decrease muscle protein degradation (Koopman et al. 2007). Additionally, the consumption of the amino acid leucine after resistance exercise has specifically been shown to increase protein synthesis because it acts as a signaling molecule in protein metabolism, stimulating muscle protein synthesis and inhibiting the breakdown of muscle proteins (Koopman et al. 2007; Atherton et al. 2017). Similarly, the breakdown of muscle protein following resistance exercise was found to be significantly lower in subjects consuming the carbohydrate, protein, and leucine supplement than in subjects who consumed the carbohydrate and protein supplement (Koopman et al. 2005). Leucine, isoleucine, and valine are the branched chain amino acids (BCAAs). During prolonged endurance exercise, when glycogen stores are low or depleted, skeletal muscle can metabolize BCAAs for energy. BCAAs are also involved in the immune system. Thus, BCAA supplements have been long used by resistance athletes in an effort to reduce skeletal muscle damage and muscular fatigue (Fouré and Bendahan 2017).

A study by Vangsoe et al. examining the amino acid concentration of several different dietary protein supplements including whey, soy, and insect proteins, found that the insect protein supplement was similar in amino acid concentration to soy protein (Vangsoe, Joergensen, et al. 2018). Vangsoe et al. observed that insect protein isolate was able to increase the concentration of all essential amino acids, leucine, and BCAAs in the blood 120 minutes following consumption, indicating that insect protein meets the requirements for essential amino acids and is comparable to soy protein as a dietary protein supplement (Vangsoe, Joergensen, et al. 2018). As mentioned previously, house crickets and other insects in the Orthoptera group have been shown to have similar levels of leucine as animal protein sources, thus cricket powder combined with carbohydrate may have the potential to increase muscle protein synthesis and decrease muscle protein degradation if used as a dietary protein supplement following resistance exercise (Churchward-Venne et al. 2017). Another study by Vangsoe et al. exploring the effect of insect protein supplementation on fat-free and bone-free mass and muscle strength following resistance training in healthy, well-nourished young men (Vangsoe, Joergensen, et al. 2018). They found that muscle strength and fat-free and bone-free mass both increased in subjects who consumed an insect protein supplement with 8 weeks of resistance training, although, they observed no significant difference in muscle strength and fat-free and bone-free mass in subjects who consumed the insect protein supplement and those who consumed an isocaloric carbohydrate supplement (Vangsoe, Joergensen, et al. 2018). Nonetheless, the findings of this study and the other study by Vangsoe et al. may indicate the potential of using insect protein supplements as a dietary protein supplement for the elderly to build muscle mass. Older adults tend to consume less than the recommended 0.8 g/kg/day of protein, which places them at an increased risk of sarcopenia (Evans 2004). Resistance exercise may be prescribed to older adults in order to help them increase muscle mass to prevent sarcopenia and the combination of dietary protein supplements with resistance exercise may further enhance muscle mass (Evans 2004). More research into insect protein supplementation and whole insects in different populations is warranted to understand their physiological and ergogenic effects.

Consumer acceptance

While edible insects could provide both a plethora of health benefits, and act as an environmentally sustainable nutrient source if used as a substitute for traditionally consumed animal products, the consumer acceptance of insect foods tends to be low in Western countries (Hartmann and Siegrist 2017; Lammers, Ullmann, and Fiebelkorn 2019). According to Hartmann and Siegrist's review of the current findings surrounding the consumer acceptance of insect foods, Western countries have shown a low willingness to consume insects as a meat substitute (Hartmann and Siegrist 2017). Another study by Lammers et al. surveyed 516 men and women from Germany and found that only 15.9% of participants were willing to consume unprocessed insects; however, 41.9% of participants reported that they would be willing to consume an insect burger containing processed insects

Table 1. Health benefits of edible insects.

Source	*Model*	*Dose*	*Effects*	*Reference*
Gb glycosaminoglycan (GbG) extracted from *Gryllus bimaculatus* (field cricket)	Freund's adjuvant (CFA)-treated male SD rats (a paw edema model) were fed a GbG-containing diet for 14 days.	2 and 10 mg/kg GbG treatment given in phosphate buffered saline	GbG treatment inhibited C-reactive protein (CRP) and rheumatoid factor, and suppressed a number of inflammatory biomarkers.	Ahn et al. 2014
GbG extracted from *Gryllus bimaculatus* (field cricket)	14-week-old male Wistar rats were fed a high-fat diet with GbG supplements for 1 month.	5 mg/kg GbG treatment and 10 mg/kg GbG treatment given in phosphate buffered saline	GbG treatment inhibited CRP, causing a reduction in edema. Abdominal and epididymal fat were reduced in rats receiving GbG treatment. Total cholesterol, phospholipids, and glucose levels were reduced in the GbG groups in a dose-dependent manner. GbG had an antihyperlipidemic effect in the rats.	Ahn et al. 2016
GbG extracted from *Gryllus bimaculatus* (field cricket)	12-week-old male diabetic (Db) mice were fed a normal rodent diet with GbG supplements for 1 month.	5 mg/kg GbG treatment given in phosphate buffered saline	GbG treatment reduce blood glucose levels within the first week of treatment. Alkaline phosphatase and LDL cholesterol levels were inhibited in rats receiving GbG treatment. Diabetic mice receiving GbG treatment had reduced protein carbonyl content and hepatocellular biomarker levels. GbG increased the anti-oxidative activities of superoxide dismutase, catalase, and glutathione peroxidase.	Ahn et al. 2019
Hermetia illucens (black soldier fly) larvae meal	Laying hens were fed either *H. illucens* larvae meal or soybean meal for 21 weeks.	108.31 ± 3.11 g/d/hen of *H. illucens* larvae meal was given to the insect meal group and 125.80 ± 1.96 g/d/hen of soybean meal was given to the soybean meal group	Significant increases in microbial diversity were found in the guts of hens receiving the insect meal. Significant increases were found in short chain fatty acid production in hens receiving the insect meal. Reductions in feed intake, serum cholesterol, and triglycerides were observed in hens receiving insect-based diets.	Borelli et al. 2017
Tenebrio molitor (mealworm) larvae meal	30-day-old male Shaver brown broiler chickens were fed either *T. molitor* larvae meal or soybean meal for 32 days.	*T. molitor* larvae meal and soybean meal were isoproteic and isoenergetic and only differed in protein source, with the insect-based diet containing 296.5 kg/ton of *T. molitor* larvae and the soybean diet containing 446.5 kg/ton of soybean meal	Feed conversion ratio improved after day 45 in broilers receiving the insect-based diet. A lower albumin-to-globulin ratio was observed in broilers who were fed the insect-based diet, suggesting an increase in immune response.	Bovera et al. 2015
Hermetia illucens (black soldier fly) partially defatted larvae meal	Rainbow trout were fed either a control diet of fishmeal (Hi0), a 25% *H. illucens* larvae meal and 75% fishmeal diet (Hi25), or a 50% *H. illucens* larvae meal and 50% fishmeal diet (Hi50) for 78 days.	Hi0 received 60 g/100 g dry matter of fishmeal, Hi25 received 20 g/100 g dry matter of *H. illucens* larvae meal and 45 g/100 g dry matter of fishmeal, and Hi50 recieved 40 g/100 g dry matter of *H. illucens* larvae meal and 30 g/100g dry matter of fishmeal	Microbial diversity, structure, and composition increased in rainbow trout receiving the insect-based diet. Organosomatic indices and fillet yields were the same in rainbow trout receiving the insect-based diet, as in those receiving the control diet.	Bruni et al. 2018
Tenebrio molitor (mealworm), *Musca domestica* (housefly) larvae and *Zophobas morio* (superworm)	144 early-weaned piglets received a maize and soybean–based diet supplemented with plasma protein powder or insects for 56 days.	5% powder of *Tenebrio molitor*, *Musca domestica* larvae and *Zophobas morio*	Diarrhea rates in all of the insect groups from Days 15 through 28 were decreased compared with those in the control group. Decreased albumin protein levels were observed in *Zophobas morio* meal group after 56 days compared to the control.	Ji et al. 2016
Hermetia illucens (black soldier fly) larvae	24-week-old laying hens were fed either H. illucens larvae meal or soybean meal for 21 weeks.	17% *H. illucens* larvae meal was given to the insect meal group and 23.5% of soybean meal was given to the soybean meal group	Cholesterol and triglycerides were lower in hens fed with *H. illucens* larvae meal. Blood levels of calcium were higher in insect-fed hens.	Marono et al. 2017

(*continued*)

Table 1. Continued.

Source	Model	Dose	Effects	Reference
Whole cricket powder	A randomized, double-blind, crossover trial, with two 14-day intervention periods and a 14-day washout period between treatments for a total duration of 42 days.	20 healthy adults, aged 18–65 received the cricket breakfast meal (25 g/day dried, roasted cricket powder) for 14 days	Cricket consumption was tolerable and nontoxic at the studied dose. Increases in probiotic bacterium *Bifidobacterium animalis* and decrease in plasma TNF-α were found.	Stull et al. 2018
Insect protein isolate from lesser mealworm (*Alphitobius diaperinus*)	A randomized cross-over study, with three different protein supplementations on four separate days. Blood samples were collected at 0 min, 20 min, 40 min, 60 min, 90 min, and 120 min after ingestion of the intervention beverage.	6 healthy young men consumed a drink containing 25 g of crude protein ($\sim$100 kcal) either as whey isolate (28.7 g powder), soy isolate (27.8 g powder), insect isolate (30.5 g powder), or placebo (0 kcal) dissolved in 400 mL water.	Insect protein isolate was able to increase the concentration of all essential amino acids, leucine, and BCAAs in the blood 120 minutes following consumption.	Vangsoe, Joergensen, et al. 2018
Insect protein from lesser mealworm (*Alphitobius diaperinus*)	A randomized, controlled, single-blinded trial consisting of eight weeks of resistance training four days/week, performed as a whole-body split routine.	18 healthy young males ingested either an insect-protein bar containing 0.4 g protein/kg or an isocaloric carbohydrate bar within 1 h after each training and 1 h before night sleep on training days.	Muscle strength and fat-free and bone-free mass both increased in subjects who consumed an insect protein supplement with 8 weeks of resistance training. However, no significant difference in these markers was found in subjects who consumed the insect protein supplement and those who consumed an isocaloric carbohydrate supplement.	Vangsoe, Joergensen, et al. 2018
Tenebrio molitor (mealworm) and *Zophobas morio* (super mealworm) larvae probiotics	One-day old Ross-308 male broiler chicks was orally challenged with *Salmonella enteritidis* and *E. coli*.	0.4% *Tenebrio molitor* (mealworm) or *Zophobas morio* (super mealworm) larvae probiotics was supplemented to the basal diet	Dry mealworm and super mealworm larvae probiotics increased average daily gain, IgG and IgA levels, reduced feed conversion ratio and mortality, and effectively helped to reduce the infection of *E. Coli* and *Salmonella* in broiler chickens.	Islam and Yang 2017

(Lammers, Ullmann, and Fiebelkorn 2019). Various survey-based studies over the past several years have identified insect neophobia, a tendency to reject insect-based foods because they are considered unknown or oppose cultural norms, as a key factor in Western consumers' unwillingness to consume edible insects (Hartmann and Siegrist 2017; Lammers, Ullmann, and Fiebelkorn 2019; Megido 2016). Caparros Megido et al. investigated this concept of insect neophobia through a study involving a blind taste-test of four different burgers: a beef burger, a lentil burger, a mealworm/lentil burger, and a mealworm/beef burger (Megido 2016). Prior to tasting the burgers, 69% of the 79 student participants were curious about tasting insects and, following the study, approximately 79% of participants reported that they would be willing to consume processed insects in the future (Megido 2016). Thus, as some other studies have suggested, prior positive experiences with insect-based foods could improve consumers' willingness to consume edible insects (Hartmann and Siegrist 2017; Lammers, Ullmann, and Fiebelkorn 2019). Other likely predictors of Western consumers' acceptance of insect-based foods include preconceptions of taste, unfamiliar consistency, sensory experience, uncertainty about the origin of the food, and gender (Hartmann and Siegrist 2017; Lammers, Ullmann, and Fiebelkorn 2019). In order to increase consumer acceptance of edible insects in the Western world, consumers should be better educated and informed about the environmental and health benefits of entomophagy, and more processed insect foods should be introduced into Western diets, as the appearance and sensation of consuming processed insects tends to be less off-putting for novice consumers than eating unprocessed insects (Hartmann and Siegrist 2017; Lammers, Ullmann, and Fiebelkorn 2019). Ultimately, additional research is necessary to determine how to best introduce insects into the diets of Western consumers.

Potential hazards and risks

As with any animal and plant-based foods, it is necessary to consider the potential hazards involved in the human consumption of edible insects. Some insects may pose a risk of allergic reaction upon consumption. While insects have commonly been ingested by individuals in many different cultures throughout the years, there have been some cases of anaphylactic shock and mild allergic reactions that were possibly associated with the consumption of insects such as caterpillars, silkworms, and cochineal insects (Belluco et al. 2013). The consumption of house crickets and other insects containing tropomyosin, a protein commonly found in both shellfish and some insects, may pose a greater risk of allergic reaction in those who are allergic to shellfish or sensitive to tropomyosin (SLU, S.U.o.A.S, 2018). Some insects such as houseflies and beetles may be capable of carrying potentially harmful bacteria; however, there has been little research on the transmission and effects of these bacteria from insect consumption in humans (Belluco et al. 2013). Microbiota such as *Listeria*, *Bacillus*, and *Clostridium*, which can be commonly sequenced from house crickets may be reduced and prevented through proper processing methods such as boiling, blanching, or frying the insects before consumption (SLU, S.U.o.A.S, 2018). Additionally, according to Belluco et al., preparing insects by boiling them and keeping them refrigerated prior to roasting them for consumption, may be a sufficient method for the prevention of bacterial growth, which may make them safer for ingestion (Belluco et al. 2013). Altogether, there is a low risk for viruses, parasites, and fungi with house cricket consumption; however, the proper processing and farming of insects prior to human consumption could help to prevent and reduce these and other bacterial, chemical, and parasitical risks involved in insect ingestion (Belluco et al. 2013; SLU, S.U.o.A.S, 2018). Additional research is necessary to determine the specific potential allergenic, microbial, and parasitical risks involved in human insect consumption.

Conclusion

The inclusion of edible insects in human diets has the potential to benefit both the environment and human health. By substituting other animal and plant foods with edible insects, resources such as land and water could be conserved, greenhouse gas emissions may be reduced, and issues of food security may be addressed. The nutrient composition of edible insects like the house cricket– a sufficient amount of essential amino acids, unsaturated fats, fiber, vitamins, and minerals, including vitamin B_{12}, iron, zinc, and calcium– may make them a suitable alternative to animal and plant foods, such as pork, chicken, and beef in human diets. The nutrient profile of edible insects may lend them to benefit human health through their consumption by potentially improving gastrointestinal health, increasing immune function, decreasing the risk of bacterial infection, and even reducing chronic inflammation that may be associated with cancer and cardiovascular disease. The high protein and amino acid content of insects may also allow them to be used as dietary supplements in combination with resistance exercise for the elderly and those attempting to build muscle mass, however more research is warranted in this area. While additional research is needed to determine any possible risks or hazards that may be associated with the human ingestion of insects, there are many positive health and environmental implications associated with edible insects such as the house cricket that should be further explored. Future research in the area of edible insects should aim to study the nutritional effects of an insect supplement in human diets in comparison to animal-based foods. For example, studies might investigate the effects of edible insects compared to a red meat and/or processed meat control group in preventing colorectal cancer in animals or humans. Future studies in meat substitutes and exercise could explore the physiologic effects of insect protein isolates combined with resistance exercise in older adults and females. Overall, edible insects offer a wide variety of potential positive nutritional and environmental implications and there are various avenues available for further exploration into the inclusion of edible insects in the human diet.

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