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REVIEW

Sericulture and the edible-insect industry can help humanity survive: insects are more than just bugs, food, or feed

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Abstract The most serious threat which humans face is rapid global climate change, as the Earth shifts rapidly into a regime less hospitable to humans. To address the crisis caused by severe global climate change, it will be necessary to modify humankind's way of life. Because livestock production accounts for more than 14.5% of all greenhouse gas (GHG) emissions, it is critical to reduce the dependence of humans on protein nutrients and calories obtained from livestock. One way to do so is to use insects as food. Compared with typical livestock, farming edible insects (or "mini-livestock") produce fewer GHG emissions, require less space and water, involve shorter life cycles, and have higher feed conversion rates. It has been recently reported that consumption of certain insects can prevent or treat human diseases. This review goes beyond entomophagy to entomotherapy and their application to the food industry.

Keywords Entomophagy · Entomotherapy · Sustainable · Low-carbon diet

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Introduction

Global climate change threatens human survival. The strongest contributor to climate change is the rapid increase in emissions of atmospheric greenhouse gases (GHGs), including CO_2, N_2O, NH_3, and CH_4. The major source of GHG is the energy sector (EPA, 2021). Increasing levels of GHGs cause not only higher average temperatures, but also increases in regional average temperature deviations. The possibility of food crises caused by climate abnormalities in the near future is increasing annually. To mitigate this threat will require changes in agricultural production methods as well as a reorganized industry that uses renewable energy sources that do not generate GHGs (EPA, 2021; Gerber et al., 2013).

The livestock industry is responsible for most of the GHGs associated with agriculture. Large quantities of GHG are emitted to raise livestock, and the industry consumes vast amounts of water (Gerber et al., 2013; Rojas-Downing et al., 2017). The industry is responsible for 14.5% of global GHG emissions (Gerber et al., 2013). However, as standards of living improve due to economic development, demand for high-quality meat and dairy products is increasing rapidly. Although 77% of the world's total arable land is used to produce feed for livestock, livestock accounts for only 18% and 37% of the planet's calorie and protein supply, respectively (Ritchie, 2019). To address this imbalance, it will be necessary to develop agricultural products that can supply high-quality protein and more calories with greater efficiency than is currently demonstrated by the livestock industry.

More than 2300 species of insects are used as food and feed around the world. The main regions where insects are used as food or feed are the tropical regions of Southeast Asia, Africa, and Central and South America, the economies of which have yet to fully develop (van Huis, 2013; van Huis et al., 2013). Although public attitudes toward the consumption of edible insects has changed in recent years, the use of insects for food and feed in Western countries remains rare or limited. Meat or poultry produced from general livestock farms is consumed by most humans without hesitation, but acceptance of edible insects varies greatly among peoples and cultures (van Huis and Oonincx, 2017). In recently developed regions where insects are consumed as food, demand and preference for insect foods are decreasing because of the reduction of forests and grasslands and the westernization of eating patterns. Recent research has focused on developing edible insect products that can be consumed without disgust or hesitation (Hanboonsong et al., 2013). In addition, discussions of the healthful aspects of insect foods in traditional Asian medical texts are being used by researchers studying the use of insects to prevent or treat various human diseases (Kim et al., 2019a; Koh, 2020). Studies on the therapeutic effects of pet insects that provide psychological stability to humans are also being conducted (Kim et al., 2019b, 2018). These studies strongly suggest not only that edible insects can be used as a new food source that can adapt to climate change, but that certain insects can heal human diseases and enhance human health. This review summarizes the research on insects that improve human health.

Entomophagy: eating and enjoying edible insects

Humans have been eating insects since prehistoric times. The consumption of edible insects is presumed to have begun between 30,000 to 7000 years ago (Schabereiter-Gurtner et al., 2002; Tang et al., 2019). Relics and records of insect farms suggest that Europeans have been keeping bees for at least 9000 years (Roffet-Salque et al., 2016), and silkworms have been bred in China for about 5000 years (Kim et al., 2019a; Koh, 2020). In the West, Aristotle's (384–322 BC) Historia Animalium references consumption of cicada females, and Pliny the Elder (77 AD) mentions that the larvae of the great Capricorn beetle (*Cerambyx cerdo*) were popular foods in Imperium Romanum in his work Natural History (van Huis, 2013; van Huis et al., 2013). As records of eating insects appear in variety of ancient documents, we can assume that prehistoric hunter-gatherers consumed insects as food because they were easier to collect than large wild animals.

More than 2300 insect species are consumed worldwide (Govorushko, 2019; Mitsuhashi, 2016; van Huis, 2013; van Huis et al., 2013). Approximately 2.5 billion people eat insects, primarily in China, India, Thailand, Korea, Japan, Mexico, Brazil, and countries in Africa. The country that consumes the greatest diversity of insect species as food is Mexico, where more than 549 insect species are eaten, followed by China, with 324 species (Govorushko, 2019; Mitsuhashi, 2016). In addition, various insect species are eaten in Africa, Southeast Asia, and Central and South America. When edible insects are divided according to order, members of Coleoptera are the most common, accounting for a total of 31.2% of all species, followed by Lepidoptera and Hymenoptera, which account for 17.1% and 15.2%, respectively. Members of Orthoptera and Hemiptera account for 13.2% and 11.2%, respectively (Fig. 1).

In most countries, more than 92% of insects used for food are collected from the wild (Yen, 2015). Those collected from forests and pastures in tropical or subtropical regions

Fig. 1 Number of edible insect species by insect order (Shahbandeh, 2018)

are distributed through markets after simple processing, such as drying, steaming, or frying (Hanboonsong et al., 2013) (Table 1). An estimated 194 species of insects are consumed in Thailand. A total of 7500 tons of insects is consumed annually in Thailand, a figure that includes species collected or farmed in neighboring Myanmar, Laos, and Cambodia (Hanboonsong et al., 2013; Sirimungkararat et al., 2010). In China, which has long consumed more than 324 species of edible insects, unique regional dishes have been developed according to the shape, size, and quality of the species. For example, Tofu with ants is popular in Heilongjiang Province, dishes using silkworm are common in Jilin Province, dishes using Cordyceps can be found in Qinghai Province, and duck meat with Cordyceps is sold in Jilin Province. Research on entomotherapy and entomophagy has been conducted in recent years (Feng et al., 2018) (Table 1). In Japan, more than 117 species of insects, including grasshoppers, have been consumed for many years (Sun-Waterhouse et al., 2016), but no research into the industrialization of edible insects is currently taking place. Events related to edible insects are recognized by relatively few consumers. Mulberry silkworms are currently cultured only to produce silk used in making traditional clothes (Kim et al., 2014) (Table 1). In Korea, edible insects such as silkworm pupae, cicadas, grasshoppers, beetle larvae, and water moths were consumed through the 1970s when other food supplies were scarce. Recently, snacks of rice grasshoppers, mealworms, and silkworm pupae have become more common. There is little demand today for insect food due to improvements in living standards, although the market for entomotherapy is growing (Kim et al., 2014; Mitsuhashi, 2016) (Table 1).

Mexican and Brazilian consumers have long enjoyed various types of edible insects. In Mexico, gusanos (maguey worms), jumiles (stink bugs), chicatanas (giant winged ants), escamoles (ant larvae), ahuatle (water-fly eggs), cuchamas (green caterpillars), chapulines (grasshoppers), libelulas (dragonflies), and escarabajos (beetles) are the preferred edible insects (Tang, 2022). Brazil enjoys abundant species diversity in the Amazon rainforest, where nutrient-rich beetles, bees, wasps, ants, butterflies, moths, and termites are eaten. The most popular edible insects in Brazil are Hymenopterans, including ants, bees, and wasps, which collectively account for 63% of the total, followed by Coleopterans, at 16%, and Orthopterans, at 7% (Tunes, 2020) (Table 1).

Consumption of edible insects is more common in Africa than elsewhere in the world. Caterpillars, termites, locusts, grasshoppers, crickets, ants, bees, bugs, and beetles are consumed in Cameroon, the Central African Republic, Congo, Nigeria, the Republic of Congo, South Africa, Uganda, Zambia, and Zimbabwe. Most of the edible insects consumed in Africa are collected from the wild (Niassay and Ekesi, 2021). In recent years, attempts have been made to farm insects in Africa. Small-scale farming of black soldier flies (BSFs) is being tried by individual farmers, and large-scale factory farming is being pursued by industry (Filou, 2021). Popular edible insects in Zimbabwe are wild-harvested mopane worms (*Gonimbrasia belina*), termites (*Macrotermes natalensis*), and crickets (*Acheta domesticus* and *Gryllus bumaculatus*). Cricket farming has been initiated, but it will take time for farm-raised crickets to reach commercial markets (Musundire and Sundin, 2019) (Table 1).

Edible insects have long been consumed in the northern regions of India (Poshadri et al., 2018). Red ant larvae (Armroli poruar tup) are consumed by Assam's indigenous communities during their principal spring festival, Bohag Bihu. Aquatic insects collected from rivers are also important edible insects. Among them, giant water bugs (jebang-kori, *Lethocercus indicus*) are consumed in large quantities. Mulberry and wild silkworms, crickets, beetles, bees, wasps, grasshoppers, locusts, termites, and dragonflies are also consumed in India (Akhtar, 2020; Poshadri et al., 2018) (Table 1).

Mini-livestock farming: a potential source of high-quality protein for food and feed

The global market for edible insects is predicted to grow by 23.8% annually from US$406.32 million in 2018 to US$1181.6 million in 2023 (Shahbandeh, 2018) (Fig. 2). Sustainable farming of mini-livestock is essential for continued growth of the edible insect industry. As of 2014, 92% of edible insects sold on the market were wild-collected, 6% were semi-domesticated, and the remaining 2% were farmed (Yen, 2015).

The majority of mini-livestock raised worldwide is silkworms, honey bees, crickets, beetles, and flies. Silkworms raised in 60 countries around the world are mulberry silkworms (*Bombyx mori*), which use pupae, a by-product of silk production, as food. In addition to the mulberry silkworm, the larvae and pupae of wild silkworms such as *Antheraea pernyi*, *Antheraea yamamai*, and *Caligula japonica* are used for food in India and China. They are also being kept as pets (Das et al., 2020; Sharma and Kapoor, 2020).

In both Asian and Western countries, farmed crickets are transformed into food ingredients and used to manufacture packaged foods, including energy bars, pasta, and chips (Reverberi, 2020). Current methods of cricket farming can be divided into a small-scale cricket farming system known as a Thai-style method that produces only crickets and a factory-type method that produces flour after farming crickets on a large scale (Hanboonsong et al., 2013). Large-scale cricket farming is carried out in the Netherlands and Canada. Farmed crickets are also used to replace fishmeal (Mohd Taufek et al., 2018).

Table 1 Insect species eaten or registered as food in various countries

Nation	Number of species	Edible insects: popular or registered as food
Angola (Lautenschläger et al., 2017)	38	*Cirina forda, Imbrasia epimethea*, *Imbrasia obscura, Imbrasia truncata* Aurivillius, *Gonimbrasia* (*Nudaurelia*) *alopia*, *Gonimbrasia* (*Nudaurelia*) *dione, Pseudantheraea discrepans*, *Micragone cana, Anaphe panda, Anaphe venata* Butler, *Notodontidae* sps, *Sciatta inconcisa* Walker, *Gastroplakaeis rubroanalis* Wichgraf, *Rhynchophorus phoenicis, Brachytrupes membranaceus*
Botswana (Obopile and Seeletso, 2013)	27	Mopane worm (*Imbrasia belina* Westwood), arrow sphinx (*Lophostethus dumolinii* Angas), harvester termite (*Hodotermes mossambicus* [Hagen]), African thief ant (*Carebara vidua* F. Smith), red locust (*Normadacris septemfasciata* Serville), brown locust (*Locustana pardalina* Walker), desert locust (*Schistocerca gregaria* Forskal), pallid emperor moth (*Cirina forda* Westwood), scarab larvae (*Oryctes boas* Fabr.), common stick, grasshopper (*Acrida acuminata* Dirsh.), honey bee (*Apis mellifera L.*), cicada (*Monomatapa insingnis* Distant), stingless bee (*Plebeina hildebrandti* Friese, *Hypotrigona gribodoi* Magretti), elegant grasshopper (*Zonocerus elegans* Thunb.), convolvulus hawk moth. (*Agrius convolvuli* L.)
Brazil (Costa-Neto, 2013)	135	Nymphs (in the rainy season) and adults (in the dry season) of *Rhammatocerus schistocercoides* (Rehn), grasshoppers, the abdomen of red ants (probably *Atta sexdens* Linnaeus), termites (dáane, keétto, maáki, kanaliére), ants (kaiwiri, kadáadali, píite, kóowhenai), beetles (móodi, haliére, déeto), caterpillars (kadaá-pali and six more), leafhoppers (tsiiríto, máami), and crickets (dzíiro)
Central African Republic (Niassay and Ekesi, 2021)	96	Caterpillars, termites, crickets and palm weevils
China (Feng et al., 2018)	324	Silkworms (*Bombyx mori* L.) and tussah silkworms (*Antheraea pernyi* Guerin-M´eneville), Mealworms (*Tenebrio molitor* L.), ants (*Polyrhachis dives*), The cicada slough of some species and the adult (*Aspongopus chinensis* Dalla), scale insects and stink-bugs, termites [*Odontotermes formosanus* (Shiraki)], dragonfly (*Anax parthenope* [Selys]),
Democratic Republic of Congo (Bomolo et al., 2017)	> 65	Caterpillars [*Elaphrodes lactea* Gaede, *Lobobunaea saturnus* Fabricius, *Cinabra hyperbius* (Westwood), *Bunaea alcinoe* (Stoll), *Cirina forda* (Westwood), *Imbrasia rubra* Bouvier, *Gonimbrasia richelmanni* Weymer, and *Athletes semialba* (Sonthonnax)], termites (*Macrotermes falciger* Gerstäcker), a grasshopper (*Ruspolia differens* Serville)
India (Sushma, 2019)	303	Silkworms (*Bombyx mori,* Antheraea mylitta*, A. proyeli, Philosamia ricini*, *Antheraea assamensis*), giant water bugs (a.k.a. jebangkori, *Lethocercus indicus*), crickets, beetles, bees, wasps, grasshoppers, locusts, termites, and dragonflies
Japan (Sun-Waterhouse et al., 2016)	> 117	Grasshoppers, honeybee drone larvae, the larvae of yellow jacket wasps (*Vespula* and *Dolichovespula* spp.; hebo), silkworm pupae
Korea, Republic of (Kim et al., 2014)	> 25	Grasshoppers (*Oxya japonica Thungberg*), silkworm larvae and pupae (*Bombyx mori, L.*), *Bombyx batryticatus*, mealworm larvae (*Tenebrio molitor* L.), white-spotted flower chafer beetle larvae (*Protaetia brevitarsis*), the Japanese rhinoceros beetle larvae (*Allomyrina dichotoma*), two-spotted cricket (*Gryllus bimaculatus*), giant mealworm beetle larvae (*Zophobas atratus*), honey bee drone pupae (*Apis mellifera* L.)
Mexico (Tang, 2022; van Huis, 2013; van Huis et al., 2013)	549	gusanos (maguey worms), jumiles (stink bugs), chicatanas (giant winged ants), escamoles (ant larvae), ahuatle (water-fly eggs), cuchamas (green caterpillars), chpulines (grasshoppers), libelulas (dragonflies), escarabajos (beetles)

Table 1 (continued)

Nation	Number of species	Edible insects: popular or registered as food
Nigeria (Alamu et al., 2013)	40	Termites (*Macrotermes nigeriensis, Macrotermes bellicosus, Macrotermes natalensis*), crickets (*Brachytrupes membranaceus, Gymnogryllus lucens, Gryllotalpa africana*), grasshoppers (Cytacanthacris naeruginosus, Zonocerus variegatus), weevils (Rhynchophorus phoenicis, Heteroligus meles), beetles (*Analeptes trifasciata, Aphodius rufipes, Oryctes boas, Oryctes monoceros, Heteroligus meles*), honey bee (Apis mellifera), african silkworms (*Anaphe venata, Anaphe infracta, Anaphe recticulata*), caterpillars (*Bunaea alcinoe, Lepidoptara litoralia, Cirina forda*), and a stink bug (*Nezara viridula*)
Thailand (Hanboonsong et al., 2013; Sirimungkararat et al., 2010)	194	Bamboo caterpillars (*Omphisa fuscidentalis*), house crickets (*Acheta domesticus*), giant water bugs (*Lethocerus indicus*), grasshoppers, and palm weevils (*Rhynchophorus ferrugineus*)
South Africa (Hlongwane et al., 2021)	50	Caterpillars (*Gynanisa* caterpillar, *Imbrasia belina,* Cirina forda), termites (*Macrotermes* species), stink bugs (*Encosternum delegorguei*), grasshoppers (*Locustana* and *Zonocerous sp.*), bees (*Carebara vidua*), and true bugs (*Cicadoidea* spp)

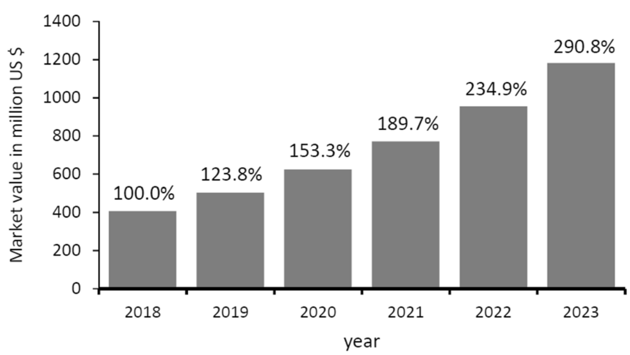

Fig. 2 Projected global market values of edible insects from 2018 to 2023 (Shahbandeh, 2018)

The mealworm (*Tenebrio molitor*) is one of the most economically important edible insects for both large- and small-scale mini-livestock farming. Mealworms produced in many countries around the world are used as protein additives in pet feed, fishmeal, and human food (Grau et al., 2017; Ribeiro et al., 2018). Mealworms have crude protein and fat contents of 13.68% to 22.32% and 8.9% to 19.94% in their edible parts, respectively. They also contain large amounts of unsaturated fatty acids, vitamins, and rare minerals such as zinc and magnesium (Nowak et al., 2016), making them a valuable substitute for fish meal and soybean meal for livestock and aquacultural operations. The world's largest vertical insect farming factory, which was completed on May 6, 2021, in northern France (Tyler, 2021), was scheduled for expansion by the end of 2021, with a goal of producing up to 200,000 metric tonnes of insect-based ingredients per year. One-third of the insect-based ingredients produced there will be used to make pet or fish feed, and the other two-thirds will be used as fertilizer.

If the market for farm- or factory-raised crickets and mealworms currently used for food in many countries is to expand, the safety of the feed used for breeding edible insects must be secured. Agricultural products must be free of toxic chemicals and heavy metals, and livestock products must not be contaminated with zoonotic infectious diseases such as prions, viruses, or other micro-organisms (Grau et al., 2017).

Another popular farm-raised insect species is the black soldier fly (BSF), which can convert livestock manure waste into valuable biomass. A recent mass-breeding study found non-significant differences in weights of BSF larvae fed poultry, swine, or dairy manure wastes compared with those fed a control Gainesville diet (50% wheat bran, 30% alfalfa, and 20% corn) (Miranda et al., 2020). BSFs are economically attractive because they can be raised in small farms or large factories using most food or agricultural wastes, including manure. For example, in Kenya, approximately 3000 tonnes of BSF are produced per year as livestock feed, replacing fishmeal. This substitution helps protect fish stocks, and the excrement produced during BSF farming is an excellent fertilizer, providing another source of income for farmers (Filou, 2021). BSF larvae contain higher levels of crude protein (42%) and fat (29%) compared with most other insects, and mycotoxins or pesticides do not accumulate in their bodies (Wang and Shelomi, 2017). However, to use BSF larvae raised on manure or food waste as human food rather than livestock feed, a variety of scientific, medical, social, and ethical hurdles must be overcome.

Apiculture is an important insect-based business. Scientific evidence of the storage of honey in pottery vessels used in Europe 9000 years ago (Roffet-Salque et al., 2016) and cave paintings more than 8000 years old that depict the collection of honey have been found (Nayik et al., 2014). From beekeeping, humans can obtain honey, royal jelly, honeydew, pollen, propolis, and beeswax. The global market for apiculture was estimated at US$9.5 billion in 2020 and is expected to reach US$11.8 billion by 2026 at a compound annual growth rate of 3.6% (Ali, 2021).

Entomotherapy: let insects be thy medicine

Although its origins are controversial, the most famous sentence linking nutrient deficiency and human diseases is "Let food be thy medicine, let medicine be thy food." Instead of focusing on who first used this sentence, we can assume from its existence that humans knew by the fifth century BC that many diseases are caused by an imbalance of nutrients (Cardenas, 2013). Even during periods when food was scarce because of a lack of agricultural technology, such as crop-protection agents and chemical fertilizers, insects have been used not only for emergency food, but also for treatment of diseases. Folk traditions involving the use of insects or their byproducts to treat human diseases have been passed down around the world in what is called "entomotherapy" (Kim et al., 2019c; Tang et al., 2019).

In China, more than 300 insect species have been used in at least 1700 classical Chinese medicine prescriptions (Czaja, 2019; Feng et al., 2018, 2009). For example, adult dragonflies, fish moths, scarab larvae, mantis egg cases, cicadae nymph exuviae, shellac of lac insects, white waxes of white-wax scale bugs, insect defensive secretions, venoms of bees and wasps, and *Hepialus* larvae infected by *Cordyceps* fungi are well-known insect-derived medicines in China. The pharmaceutical uses of insects include antibiotic, anti-inflammatory, anti-tumor, immune regulation, anti-sensitivity, antioxidant, and hypoglycemic activities.

More than 50 species of insects have long been used to treat human colds, indigestion, arthritis, abdominal pain, and skin diseases in Nagaland, in northern India. Blister beetles in particular are reportedly effective in treating skin diseases (Mozhui et al., 2021).

In Europe, the record of treating human diseases using insects is lengthy. Pliny the Elder mentioned using insects for treating human diseases in Naturalis Historiae. Insects from the orders Coleoptera, Hymenoptera, Orthoptera, and Hemiptera were used to treat indigestion and disease of the skin, respiratory system, genitals, circulatory system, nervous system, muscular system, and immune system (Chantawannakul, 2020). Pedanius Dioscorides mentions the treatment of diseases using insects in his books De materia medica and On Poisonous Animals. For example, bed bugs were used to treat four-day fever, fried cockroaches were prescribed for ear pain, fried cicadas for back pain, and grasshoppers and locusts for the treatment of anuria in women (Chantawannakul, 2020).

In the northern Bahia region of Brazil, more than 42 species of insects are used as folk remedies for headaches, dizziness, asthma, colds, arthritis, eye diseases, and snake bites (Costa-Neto, 2002). More than 210 insect species are used in folk medicine in Mexico, with the most used belonging to the orders Coleoptera, Hymenoptera, Orthoptera, and Hemiptera. For example, ants are used to treat arthritis and chickenpox, and crickets to treat urinary system diseases.

In Africa, insects are widely used in folk medicine (Chantawannakul, 2020; Costa-Neto, 2005). Cricket-gut extracts are used to treat skin wounds in Nigeria, and honey is used to treat depletion of energy throughout Africa. Termites are used to treat wounds, and wasps and white ants are ground together with their homes for consumption by pregnant women in Somalia. Locusts are ground and used to treat headaches in Zaire and to treat high blood pressure in Zambia. In South Africa, locusts are used to relieve malnutrition and treat nightmares in children.

In Korea, insects have long been used to cure diseases. Medicines based on insects are described in a Korean traditional medical text (Donguibogam in Korean) (KIOM, 2021). Donguibogam describes how to cure diseases and maintain health using 25 insect-derived drugs. Among them, white bee honey is used to relax the intestines and revitalize the qi (body and mental energy), eating bee cubs (Bongja in Korean) makes ease bowel movements, beeswax can be used for treatment of wounds, and beeswax can be used to heal bone fractures and muscle damage. In addition, digger wasps can reportedly treat hearing loss, and hornet nests (Nobongbang in Korean) can be used to treat skin diseases and toothaches.

Silkworm products used medicinally include *Bombyx batryticatus* (baekgangjam in Korean), which is used to remove freckles; spear scars are used to treat skin diseases; chrysalis is used to restore vitality; male silkmoths (jamja in Korean) are used to improve sexual function, dried silkworm poop (Jamsa in Korean) is used to treat paralysis, papers attached to silkworm egg shells (Jampoji in Korea) are used to treat diseases suffered by women, and new cotton (Sinmyeon in Korean) is used for female bleeding. In addition, scarab beetle larvae (Kumbangi in Korean) can be used when a wound is swollen or scalded or when a bone is fractured (Pemberton, 1999).

Preclinical and clinical research into known health-enhancement effects of insects and insect-derived materials are being conducted. Important findings to date are summarized in Table 2. Significant findings that can be applied or are sold as health supplements or functional foods are summarized in the following section.

Table 2 Insects and insect-derived materials with health-enhancement effects

Insects (references)	Developmental stage—treatment substances	Disease/functional activity
Antheraea mylitta (Dutta et al., 2017; Jena et al., 2018)	Cocoon—peptides	Anti-bacterial, antioxidant
Apis cerena (Han et al., 2015; Jang and Song, 2013; Ko and Song, 2014; Liu et al., 2016; Yang et al., 2017)	Adult venom	Anti-tumor, anti-inflammation, anti-bacterial, skin wrinkle improvement
Apis mellifera (Hegazi et al., 2013; Izuta et al., 2009; Lee et al., 2005; Lerrer et al., 2007; Li et al., 2009; Okamoto et al., 2003)	Adult venom Royal jelly Propolis	Localized plaque psoriasis, degenerative arthritis, rheumatoid arthritis, gout, knee osteoarthritis, frozen shoulder, and lumbar disk herniation Anti-tumor, anti-angiogenesis, anti-allergic effects Anti-tumor, localized plaque psoriasis
Aspongopus chinensis Dalla (Tan et al., 2019)	Adult extracts	Anti-tumor activity
Blaberus giganteus (Kaya et al., 2017)	Adult dorsal pronota and wings	Anti-bacterial activity
Bombus adens (Yoon et al., 2017)	Adult venom sac	Anti-microbial, anti-tumor activity
Bombus consobrinus (Yoon et al., 2017)	Adult venom sac	Anti-microbial, anti-tumor activity
Bombus terrestris (Yoon et al., 2017)	Adult venom sac	Anti-microbial, anti-tumor activity
Bombus ussurensis (Yoon et al., 2017)	Adult venom sac	Anti-microbial, anti-tumor activity
Bombyx mori (Hur et al., 2005; Kim et al., 2019a; Koh, 2020; Nguyen et al., 2020, 2021, 2016)	The 3rd-day 5th-instar larvae—freeze-dried powders The 4th- to 8th-day 5th-instar larvae (mature silkworm): steamed and freeze-dried powder, a.k.a. HongJam *Bombyx batryticatus* extracts Silkworm dongchunghacho freeze-dried powder	Hypoglycemic effects Memory enhancement, Parkinson disease prevention, gastrointestinal disease prevention, liver function enhancement, skin whitening, hair growth Parkinson disease prevention Thrombolytic activity, liver and immune enhancement, anti-stress, anti-cancer activity
Calliphora vicina (Chernysh et al., 2002)	Adult hemolymph	Antiviral, anti-tumor activity
Calosoma sycophanta (Nenadić et al., 2017)	Adult pygidial glands	Anti-microbial activity
Catharsius molossus (Ahn et al., 2019)	Adult dried materials	Anti-aging, anti-tumor activity
Chrysomya megacephala (Chaiwong et al., 2016)	Larval secretion/excretion	Anti-bacterial activity
Clanis bilineata (Sun et al., 2018; Wu et al., 2017)	Larval skin, extracted oil	Antioxidant activity
Curculio caryae (Shapiro-Ilan and Mizell, 2015)	Pupae	Anti-fungal activity
Eupolyphaga sinensis (Wang et al., 2015)	Protein	Anti-tumor activity
Galleria mellonella (Zdybicka-Barabas et al., 2012, 2014)	Larvae	Anti-bacterial activity
Gryllodes sigillatus (Zielińska et al., 2018)	Adult hydrolysates	Antioxidant, anti-inflammatory activity
Hermetia illucens (Elhag et al., 2017)	The 5th instar larvae	Anti-microbial activity
Hydropsyche angustipennis (Tszydel et al., 2015)	Cocoons—silk fibers	Biomaterials for medicine
Musca domestica (Chu et al., 2011; Hou et al., 2007; Jin et al., 2010)	Third instar larvae	Anti-inflammatory, anti-bacterial, anti-tumor activity
Myrmecia gulosa (Veal et al., 1992)	Metapleural glands	Anti-microbial activity
Nasonia vitripennis (Danneels et al., 2014)	Adult venom sac	Anti-inflammatory activity
Parapolybia varia (Yoon et al., 2016)	Adult venom sac	Anti-microbial, anti-fungal, anti-tumor activity
Polyrhachis dives (Tang et al., 2015)	Adult	Anti-inflammatory activity
Polyrhachis vicina Roger (Li et al., 2020)	Extracts	Anti-inflammatory, anti-tumor activity
Protaetia brevitarsis (Choi et al., 2019)	Larval extracts	Anti-thrombotic, anti-tumor activity
Sarcophaga bullata (Itoh et al., 1985; Zielińska et al., 2018)	Larval extracts	Anti-bacterial, anti-tumor activity
Spodoptera litura (Choi et al., 2000)	Peptide	Anti-bacterial activity

Table 2 (continued)

Insects (references)	Developmental stage—treatment substances	Disease/functional activity
Tabanus bovinus (Ahn et al., 2000; Kwak et al., 2002)	DW adult extracts	Anti-angiogenic, anti-tumor, anti-inflammatory activity
Tenebrio molitor (Zielińska et al., 2018)	Larvae	Anti-bacterial activity
Tetramorium bicarinatum (Téné et al., 2016)	Adult venom sac	Anti-microbial activity
Vespa analis (Yoon et al., 2015)	Adult venom sac	Anti-microbial, anti-fungal, anti-cancer activity
Vespa crabro (Yoon et al., 2015)	Adult venom sac	Anti-microbial, anti-fungal, anti-cancer activity

The larvae of the white-spotted flower beetle and rhinoceros beetle are said to be effective folk remedies for treating liver diseases such as liver cancer and cirrhosis. A recent animal study showed that simultaneous treatment with their extracts protected hepatocytes from toxic chemicals (Chon et al., 2012). In addition, animal experiments have shown white-spotted larvae to have a thrombolytic effect (Choi et al., 2019). The insect species with the most scientifically documented health-promoting effects is mulberry silkworm. Various health-enhancement effects of silkworms have been identified at each stage of development. Freeze-dried powder derived from 3rd-day 5th-instar silkworm larvae reportedly has a hypoglycemic effect (Ryu et al., 1997, 2002), and a hot water extract of *Bombyx batryticatus* improves the survival of dopaminergic neurons in MPTP-induced Parkinson's disease rodent models (Lim et al., 2019).

Mature silkworms just before metamorphosis contain enlarged silk glands. Whole mature silkworms can be consumed by steaming and freeze-drying (Ji et al., 2015). Steamed and freeze-dried mature silkworms, also known as hongjam, are associated with various health-enhancement functions in multiple animal experiments (Ji et al., 2019, 2017a, 2016a, 2016b, 2017b; Kim et al., 2019a; Koh, 2020). It was reported that rodent models supplemented with hongjam exhibited significant improvement in memory (Koh, 2020; Nguyen et al., 2020, 2021), similar or superior to that of donepezil, a dementia drug with an inhibitory effect on the onset of Parkinson's disease (Ji et al., 2016c; Nguyen et al., 2016), improves liver function, reduces the risk of liver cancer (Cho et al., 2016), and has a protective effect on the gastrointestinal tract (Lee et al., 2017). In addition, HongJam extends the lifespan and improves the healthspan of *Drosophila* models (Kim et al., 2019a; Koh, 2020; Nguyen et al., 2016). It has been suggested that the molecular and cell biological mechanisms inducing these health-enhancement effects enhance the activity of mitochondria and activate signal transduction mechanisms in various cells, tissues, and organs (Kim et al., 2019a; Koh, 2020).

In addition to these health-promoting effects, silkworms offer other advantages over other insect species currently used in entomotherapy. The first is based on the fact that, because the epidermis of silkworm larvae is thin and soft, freeze-dried silkworms can be easily consumed by humans and animals (Ji et al., 2015). The second advantage is that silkworms eat only mulberry leaves and are sensitive to crop-protection agents or chemicals, making them impossible to breed using leaves contaminated with any chemicals, guaranteeing the safety of products made from silkworms. However, silkworm sericulture requires a field to produce mulberry leaves for feed, which requires considerable effort in a short duration, and the production costs of HongJam are high because mature silkworms must be steamed and freeze-dried before being crushed into powder. In addition to the introduction of automatization of silkworm breeding to reduce labor inputs, it will be necessary to identify alternative methods of manufacturing HongJam that require less energy input.

Climate change and rapid transition to a super-aged society in developed countries present new opportunities for sericulture and edible insect industries

Climate change has strengthened typhoons (also known as cyclones or hurricanes) (Chu et al., 2020) and increased the frequency of extreme heatwaves, droughts, wildfires, and heavy rainfalls (Gagnon, 2021). Because food production infrastructure is often destroyed by climate-related disasters, edible insects that can be raised in a short period, require small spaces, and have a higher feed conversion rates can play a pivotal role in supplying protein to humans in the future (Musundire and Sundin, 2019). Polyphagous edible insect species are anticipated to play an important role in disaster responses because they can be reared using damaged crops or trees that cannot be used for human food (Durst and Shono, 2010).

Another challenge facing developed countries is the rapid transition to a super-aged society due to the extension of life expectancy made possible by biomedical science and technology and improvements in hygiene (Kontis et al., 2017). The elderly tend to suffer from one or more degenerative diseases, resulting in a surge in health care costs (Knickman and Snell, 2002; Nghiem and Connelly, 2017; OECD, 2019). To solve these problem, it is important to increase the healthspan, the period of life without disease. Currently, the only generally accepted ways to improve healthspan is to reduce daily caloric intake and maintain a healthy body and mind through regular exercise (Testa et al., 2014). As caloric restriction and regular exercise are known to improve mitochondrial functions, an important goal of longevity pharmacology is to identify or invent chemicals or foods that can mimic the effects of caloric restriction (Ingram and Roth, 2015; Kim et al., 2019a). One of the important requirements for calorie-restriction mimetics is activation or enhancement of mitochondrial function. Recent studies on the health-promoting effects of silkworm products have found that HongJam consumption can increase the life expectancy and healthspan of experimental animals (Kim et al., 2019a; Koh, 2020; Nguyen et al., 2016), making it a functional food, with the most important role in calorie-restriction mimetics.

In conclusion, sericulture and the edible insect industry can play an important role in addressing two of the most serious problems facing humans in the near future. Insects are the oldest and most prosperous animals on Earth and will thrive regardless of human survival. Utilizing the various advantages of insects mentioned in this review, mankind should be able to find ways to adapt to impending changes in living conditions on Earth.

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Declarations

Conflict of interest Authors declared no conflict of interest.

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