



OVERVIEW ARTICLE

Research and policy priorities for edible insects

Valerie Stull¹ · Jonathan Patz^{1,2}

Received: 4 February 2019 / Accepted: 15 June 2019
© Springer Japan KK, part of Springer Nature 2019

Abstract

Global communities increasingly struggle to provide ample healthful food for growing populations in the face of social and environmental pressures. Insect agriculture is one underexplored and innovative approach. Sustainable cultivation of nutrient-dense edible insects could help boost food access, support human nutrition, and mitigate key drivers of climate change. The edible insects industry is in its nascent stages, as relatively few entities have committed resources towards optimizing farming methods. Nevertheless, insect farming is poised to benefit food insecure populations, and the planet as a whole if more targeted research and conducive policies are implemented. The purpose of this paper is to outline the state of the science regarding edible insects, define a research agenda, and recommend policy action to support the growing industry. Edible insects are not a panacea for current challenges, but they have the potential to confer numerous benefits to people and the environment. Rigorous research is needed to establish optimal farming methods, strengthen food safety, understand health impacts of consumption, explore consumer acceptance, tackle ethical considerations, and investigate economic viability. A clear definition for insects as food, industry guidance support for obtaining generally regarded as safe designation, and collaboration by industry stakeholders to develop production standards will also help move the industry forward. Generating and galvanizing knowledge sharing networks, investing in critical interdisciplinary research, and advocating for conducive policies that support emerging entrepreneurs will be necessary to capitalize on the benefits of edible insects in the future.

Keywords Sustainable food systems · Edible insects · Entomophagy · Alternative protein · Agriculture · Policy

Introduction

Global food security is improving, but remains tenuous. The current food system is increasingly constrained by finite planetary resources, inequitable food distribution, a changing climate, and growing demand for more resource-intensive protein products such as meat and dairy (Rangathan et al. 2016). By 2050, the world's population is likely to reach 9.8 billion (UNDESA 2017), requiring creative measures across the supply chain to provide adequate food for all. To satisfy projected food demand, a 60% increase in

agricultural production by weight from 2005 levels has been estimated (Alexandratos and Bruinsma 2012). However, changes in more than just agricultural yields are needed. Current livestock production practices alone account for ~14.5% of total anthropogenic greenhouse gases (GHGs) (Gerber et al. 2013), and per capita demand for protein and calories is expected to increase 100–110% by 2050 (Tilman et al. 2011). Reducing ruminant meat and dairy consumption may be a key component of combatting agricultural emissions and increasing the probability of limiting warming to within a 2 °C temperature target (Hedenus et al. 2014). Simultaneously, about 820 million people were estimated to face chronic undernourishment in 2017 (FAO et al. 2018), even though there is enough food available to feed everyone today. Roughly 1/3 of food produced globally is lost or wasted each year (Gustavsson and Sonesson 2011), which depletes freshwater resources and contributes to GHG emissions without benefiting human nutrition. Insect agriculture could help remedy these gaps while also reducing emissions from animal production.

Handled by Parikesit, Universitas Padjadjaran, Indonesia.

✉ Valerie Stull
vstull@wisc.edu

¹ Global Health Institute, University of Wisconsin-Madison, 1050 Medical Sciences Center, 1300 University Ave., Madison, WI 53706, USA

² Nelson Institute, Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, 1710 University Ave., Madison, WI 53726, USA

In the last decade, entomophagy—the practice of eating insects—has garnered increasing support from academics across disciplines, governments, industry, and development agencies for both environmental and nutritional reasons. As far back as 1975, forward thinking researchers recognized the potential value of edible insects in easing world protein shortages (Meyer-Rochow 1975). Insects are nutrient dense and typically require less land, water, and feed than conventional livestock to survive and thrive (van Huis et al. 2013) while emitting fewer GHGs (Oonincx et al. 2010). Throughout history, insects have played a critical role in human nutrition on nearly all continents (Bodenheimer 1951; DeFoliart 1995). Today, close to 2100 identified edible species are consumed across the globe (Jongema 2017), and an estimated two billion people live in countries, where entomophagy is practiced by some of the population (van Huis et al. 2013). The prevalence of insect foods globally (and their growing presence in Europe and North America) demonstrates that they are rapidly outpacing their “novelty status” and becoming a legitimate food on local, national, and regional levels (Halloran et al. 2015).

Insects are more than food. For some today, both collecting and farming insects provides an important income stream. However, the vast majority (92%) are harvested from the wild (van Huis 2013; Jongema 2014), highlighting the need for new insect agriculture or “minilivestock” cultivation as a means to sustain increased consumption rates and ensure food safety. Moreover, unsustainable wild-harvesting of edible insects is problematic in some areas and can lead to forest destruction (Roberts 1998), ecological damage (Illgner and Nel 2000), or insect resource collapse, endangering future harvests and the environment (Ramos-Elorduy 2006; Yen 2008).

In their seminal 2013 report, the Food and Agriculture Organization of the United Nations (FAO) highlighted entomophagy as one under-utilized strategy to help meet current and future nutritional needs globally (van Huis et al. 2013). While much has been written about edible insects in recent years, a more targeted effort to galvanize stakeholders around improving the regulatory and research climate is essential for realizing potential gains. Better and smarter utilization of edible insects as “minilivestock” presents an opportunity to boost protein production under increasing food system pressures, improve human nutrition while protecting ecosystems, and mitigate key climate change drivers.

The purpose of this paper is to assess the scientific evidence showing potential benefits of edible insects, identify key gaps in our understanding, and explore the policy landscape in the United States (US) and the European Union (EU). We describe four primary pathways by which insect agriculture can contribute to solving the problems outlined above, and then, we define a research agenda and recommend policy actions to facilitate the way forward.

Discussion

Minilivestock farming could help address the above challenges through four primary pathways: (1) providing important nutrients for humans; (2) improving livelihoods through production at various scales, even in low-resource settings; (3) combating climate change through the reduction of GHG emissions that stem from both protein production and food waste; and (4) generating income and value via multiple products and uses.

Pathway 1: supplying nutrients

Insects can serve as an accessible, nutrient-dense food across varied contexts. Many edible species have been touted as a good source of bioavailable protein (Verkerk et al. 2007) with crude levels comparable to and in some cases even higher than other animal protein sources (Melo et al. 2011; Belluco et al. 2013). Numerous species contain all essential amino acids for human nutrition (Bukkens 2005; Collavo et al. 2005), and many are thought to supply important nutrients, including specific amino acids, which are deficient in cereal- and legume-based diets (van Huis et al. 2013; Nadeau et al. 2015; Manditsera et al. 2019). Insects can serve as an important protein supplement to the diet, but it should be noted that not all insects are created equal—some are low in specific essential amino acids (Williams et al. 2016). Proteins found in some insects may also have functional properties useful for food processing and food formulation (Hall et al. 2017).

Edible insects are also rich in healthy polyunsaturated fatty acids, with numerous species providing ample essential linoleic and linolenic acids (Womeni et al. 2009) (Fig. 1). Lipid concentration varies by species, and some insects, such as *Acheta domesticus* crickets, have favorable polyunsaturated to saturated fatty acid ratios; others have favorable omega 6 to omega 3 ratios for human health (Paul et al. 2017). Farming edible insects may allow manipulating the nutrient content of insects via their feed, including targeted shifts in fatty acid composition to generate healthier insects.

Furthermore, insects are often a good source micronutrients, including copper, magnesium, manganese, phosphorous, and selenium (Rumpold and Schlüter 2013), as well as iron and zinc (Christensen et al. 2006) (Fig. 2). *Tenebrio molitor* larvae, *Locusta migratoria*, and *A. domesticus*, for example, have reported iron and zinc concentrations greater than chicken or pork (Finke 2002; Oonincx and van der Poel 2011; Mwangi et al. 2018). Some have argued that edible insects rich in micronutrients such as iron and zinc present an inimitable opportunity to improve the nutritional status of both Western and resource-poor groups (Mwangi et al. 2018). They may also help to combat food scarcity in

Fig. 1 Protein and fat content of insects and other animal products (% by raw weight) Sources: Insects data from (Finke 2002); beef, chicken, and eggs from (USDA 2018)

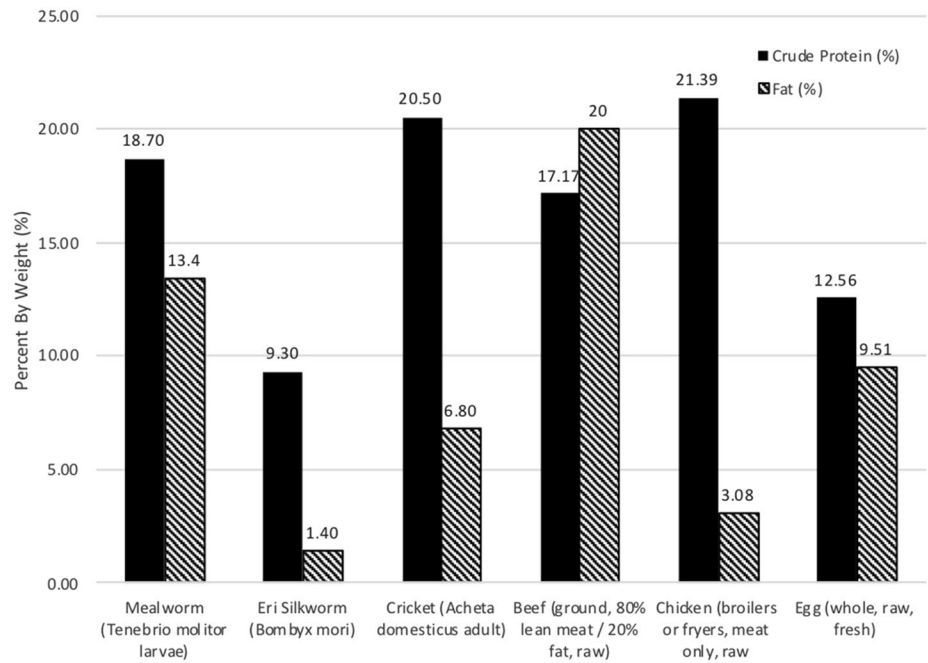
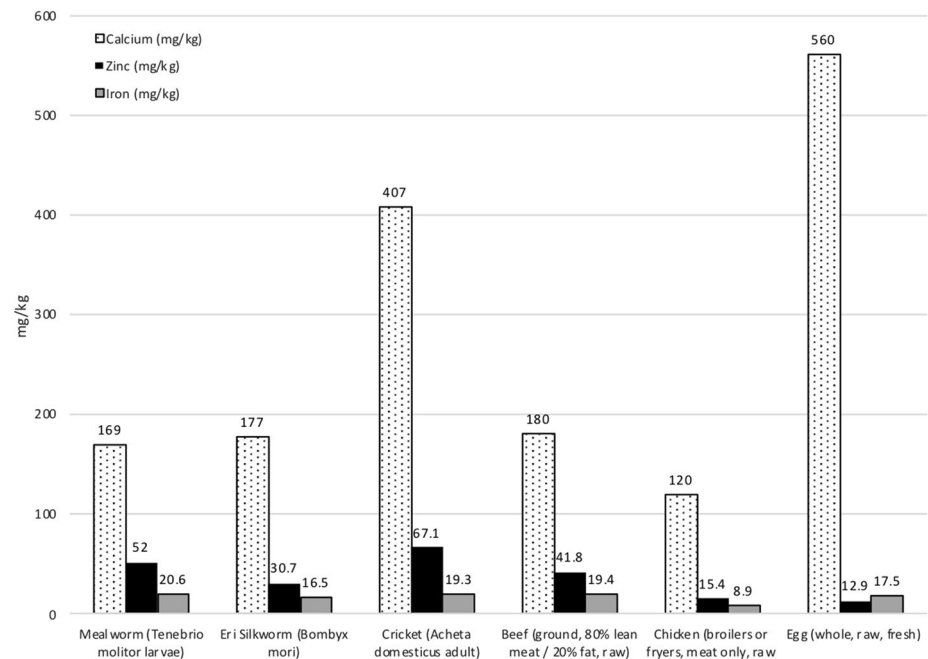


Fig. 2 Micronutrient composition of edible insects and other animal products (mg/kg raw) Sources: Insects data from (Finke 2002); beef, chicken, and eggs from (USDA 2018)

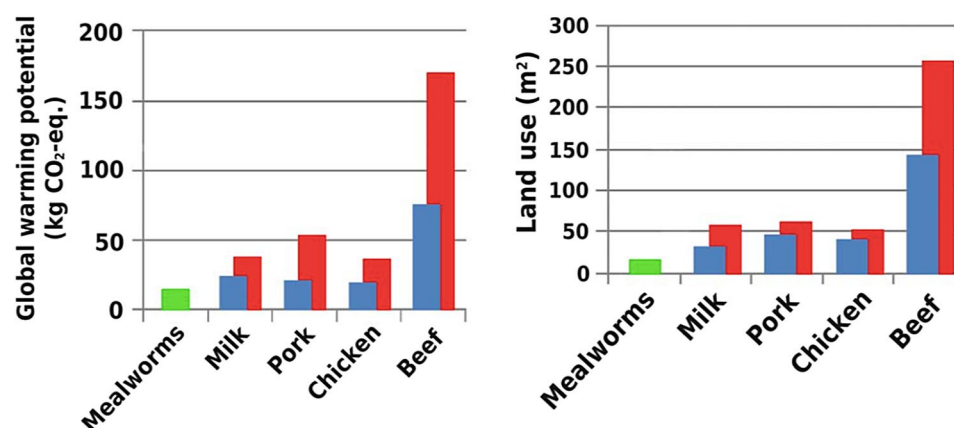


contexts where micronutrient deficiencies are problematic (Illgner and Nel 2000; Christensen et al. 2006; van Huis 2013). Limited data on the vitamin content of edible insects exist, but there are reports that some species are particularly high in B vitamins such as biotin, pyridoxine, riboflavin, pantothenic acid, folate, niacin, and cobalamin (Schabel 2010; Rumpold and Schlüter 2013; Nowak et al. 2014). From the published literature, vitamin concentrations vary

significantly across species, likely influenced by external factors including differences in feed (Payne et al. 2016).

As a food category, edible insects are quite unique and diverse. Unlike other animal products, insects contain variable amounts of dietary fiber (Finke 2007), most predominately in the form of chitin derived from the exoskeleton. Dietary fiber contributes to gut health, has been shown to increase diversity in fecal microbiota (Martínez et al. 2013; Tap et al. 2015), and is associated with a reduced risk of

Fig. 3 Environmental impact of mealworms compared to other animal products. Global warming potential from production of 1 kg of protein in kg CO₂ equivalents (left); estimated land use in m² from production of 1 kg protein (right). Minimum values in blue, maximum in red. Source: Oonincx and de Boer (2012)



several diseases (McKeown et al. 2004; Pereira et al. 2004; Farvid et al. 2016). New methods for high-accuracy insect chitin measurement have been developed considering acid detergent fiber and acid detergent lignin components (Hahn et al. 2018). It should be noted that insect chitin and nutrient composition vary greatly and are diverse compared to conventional meats; the consumption of some edible insects offers potential health benefits, while others may worsen diet-associated health problems linked to overnutrition (Payne et al. 2015).

Pathway 2: improving livelihoods

Along with their nutrient-rich composition, insects retain amenable characteristics for resource-efficient farming. First, insects tend to have higher fecundity rates than conventional livestock (Premalatha et al. 2011) and experience rapid growth, often reaching maturity faster than large animals such as beef cattle. Farmers may experience multiple harvest periods in 1 year, advancing their earning potential where markets exist. Second, insects can often be reared in tight confined spaces, allowing for the possibility of effective vertical farming designs and farming opportunities for people who do not have access to land.

With relatively short lifespans, little required technology for small-scale production, and well-understood breeding behavior, numerous species can be farmed by people of all socioeconomic and educational backgrounds. In addition, some insects are adept recyclers that can be cultivated using organic side streams, agricultural byproducts, manure, or rotting food, thereby recycling and adding value to inedible biomass (van Huis et al. 2013). This is a particularly viable option when utilizing insects as livestock feed, which is relevant but beyond the scope of this paper. This efficiency will be a valuable characteristic under mounting food system pressures, and may make insect farming affordable for resource-limited groups. The sizeable cricket industry in Thailand is an apt example of the feasibility of minilivestock

farming, as 20,000 small-scale farmers generate the majority of their household income from cricket rearing (Hanboonsong et al. 2013).

Pathway 3: combating climate change

On a global scale, insects may contribute to a climate change mitigation strategy for food production; they have the potential to reduce GHG emissions stemming from both protein production and food waste. Due to their ability to draw water out of their feed and high feed conversion efficiency, freshwater inputs and necessary land clearing to grow feed for insects are diminished compared with conventional livestock. New research posits that insect agriculture may reduce agricultural land requirements, especially in conjunction with shifts towards more resource-efficient animal foods (eggs and chicken) and food waste reduction strategies (Alexander et al. 2017). Total GHG emissions from insect cultivation, particularly methane, would be minimal compared to beef. Oonincx and de Boer (2012) estimated the global warming potential and land use required for mealworms (*Tenebrio molitor*) and compared them with reported values for conventional animal products (Fig. 3).

Emissions from food waste may also be reduced if waste is used as a feedstock for insects. The voracious larvae of the black soldier fly (BSF) *Hermetia illucens* (L.) thrive on manure and rotting food; BSF could help mitigate food waste while yielding a suitable feedstock for poultry and fish. Industrial agriculture companies such as Agriprotein in South Africa are already utilizing BSF to reduce waste and environmental contamination via runoff while generating a nutrient-dense feedstock for other livestock. Alternatively, if consumer food waste was used to feed edible mealworms (*T. molitor*), an estimated 8.1% of current animal production could be replaced (Alexander et al. 2017). Use of insects as recyclers can occur on a smaller scale as well, offering benefits to individuals and households, not just companies.

Pathway 4: generating income

Finally, edible insects can generate a variety of salable items that may support new industries of traded products. Numerous added-value products can be generated from processed insects (e.g., protein powders, oils, fibers, even medicines), while insect waste (e.g., frass) is nutrient-dense and may also be a useful fertilizer. Edible insects and insect-based food products could complement emergency food aid (as a component of ready-to-use-therapeutic foods), feed astronauts during space flight (or even be produced in space), support health for military troops, or improve household income and nutrition for enterprising smallholder insect farmers. Synchronously, edible insects represent a new realm of culinary explorations, which have only just begun (for example, see the Nordic Food Lab's recent book, *On Eating Insects*).

Reality check

Edible insects are not a panacea for current global food challenges, and we should be careful not to overstate their benefits. However, insects certainly represent a novel, burgeoning food and feed source with potential to generate bioavailable animal protein with fewer environmental consequences compared to other forms of livestock.

Skeptics should be mindful of the relative infancy of minilivestock farming compared with other established agricultural activities. Advances in animal husbandry over approximately 10,000 years have allowed farmers to exploit the genetic strengths of livestock while optimizing growth, disease resistance, and fecundity. Humans do have experience rearing insects, as sericulture has been practiced for nearly 7,000 years for silk production, and later apiculture was embraced to generate honey. Other insects, including but not limited to mealworms, waxworms, ladybugs, crickets, and moths, with valuable properties have also been cultivated in bulk on artificial and natural diets. Today, scientists and insect farmers alike are intensifying efforts to rear insects for food and feed, but infrastructure and resources still pale in comparison to those designated for traditional livestock. Just have we have with other animals, we may be able to capitalize on the strengths and benefits of insects using method refinement and domestication, while simultaneously avoiding potential negative side effects.

It would be myopic to expect all insect production systems today to be optimized in the likeness of traditional livestock, and developing minilivestock to resemble conventional systems could also be environmentally and ethically problematic. There are thousands of insect species to explore and ample existing understandings of insect biology to build from, however. Knowledge sharing between successful small-scale producers, commercial insectaries, and researchers around the globe will be useful in advancing

minilivestock-rearing techniques at all levels, elevating resource efficiency, and safeguarding health.

Research gaps and recommendations

Each of the putative benefits of insect consumption necessitates robust empirical support, including applied and system-level examinations. Narrow studies on specific insects, particularly those harvested from the wild or reared in a laboratory, make up the bulk of published entomophagy research. With investments in strategic and targeted research, we can improve models for insect-based agriculture and optimize nutrition. Research is needed in five strategic areas: (1) insect farming optimization for different scales of production; (2) food safety, nutrition, and health impact assessment of entomophagy; (3) public and consumer acceptance of edible insects; (4) ethics and social justice; and (5) the economic viability of insect agriculture.

Research recommendation 1: insect farming optimization

Efforts to optimize insect production systems are just beginning to be rigorously investigated. There is limited evidence outlining the best rearing mechanisms to augment energy efficiency, feed conversion ratio, and water use—and how these mechanisms compare to traditional livestock. More study and experimentation is needed to develop fully domesticated systems for rearing a variety of edible insect species on an assortment of feed substrates. Fundamentally, the feedstock matters, as it will impact insect nutrition and feed conversion efficiency (Lundy and Parrella 2015). Energy requirements for feedstock production will influence overall process efficiency. There may be opportunities to improve or modify nutritional profiles of insects, but this requires careful evaluation of feed inputs and nutrient cycling. Since insects can often consume biomass inedible to humans, agricultural byproducts and crop residue could serve as available, low-cost feedstocks for insects; however, the impacts of organic biomass removal on soil health must also be quantified in agricultural systems.

Small-scale insect production needs contextualized research that evaluates resources available in the local environment and edible species that would thrive on those resources. Researchers should take note of the success of small-scale producers and commercial insectaries around the globe following a positive deviance approach (Lapping et al. 2002). For small-scale operations, simple techniques to augment insect growth and nutrient content must be generated taking into account cultural requirements. For commercial production, lifecycle assessments of alternative substrates, such as food waste or agricultural byproducts (e.g., crop residues, spent grain from beer) also worthy of exploration.

Likewise, controlling temperature and humidity for large-scale production may be energy-intensive, so understanding the magnitude of these energy requirements is critical.

Research recommendation 2: food safety and nutrition

Not all insects are edible, but those that have been eaten traditionally are broadly considered safe. Insects do have the potential to transfer harmful bacteria, fungi, or parasites to humans, however, particularly if they are not acquired from hygienic environments (Grabowski and Klein 2017). While there is limited evidence of disease or parasitoid transmission from insect consumption when insects are handled under the same sanitary conditions as any other food (van Huis et al. 2013), hazards may exist that vary by production method and uncertainties about food safety remain (EFSA Scientific Committee 2015). At various points during collection, production, and processing, insects are at risk of contamination by pathogens, so establishing best practices to preserve food safety is critical for both consumer acceptability and economic viability (Meyer-Rochow 2010). These best practices should be developed from additional research and modified for variable conditions, including low-resource contexts.

Microbial research on edible insects is sparse, but recent evidence suggests that microbial quality of insects varies dramatically by species, across rearing methods, by facility, and even over production cycles at the same company (Vandeweyer et al. 2017). All insects have a complex microbial community containing mutualistic and pathogenic microbes associated with both natural and farmed environments (Marshall et al. 2016), and under certain conditions, insect microflora provides a medium for growth of undesirable microorganisms, such as the spore-forming bacterial species, *Bacillus* spp. (Klunder et al. 2012). *Bacillus* spp. can cause foodborne illness and form stress-resistant endospores (Hong et al. 2009). Not all heat treatments or preservation methods are sufficient to eliminate spores found in edible insects (Ter Beek and Brul 2010; Vandeweyer et al. 2018), engendering possible health risks to consumers. For those not accustomed to such practices, raw insect consumption is discouraged and hygienic washing and heating processes are recommended (Grabowski and Klein 2017). More research is needed to determine optimal processing methods for food safety given these risks.

A closer assessment of the allergenic potential of edible insects is also important, given that there are known antigenic determinants conserved across arthropods. Cross-reactivity between edible insects and crustaceans has been established, and current data highlight the role played by arthropod pan-allergens including tropomyosin and arginine kinase (Ribeiro et al. 2018). Specifically,

in patients with shrimp allergies, the protein tropomyosin was shown to be involved in cross-reactivity between shrimp, insects, and mites (Witte et al. 1994). Patients allergic to shrimp have reacted to *T. molitor* (mealworm) extracts (Broekman et al. 2015), and sera from people with dust mite and crustacean allergies cross-reacted with mealworm proteins (Verhoeckx et al. 2014). Researchers also found a strong correlation between *Gryllus bimaculatus* cricket-specific Immunoglobulin E (IgE) levels, shrimp-specific IgE levels, and responses, indicating that crickets may induce a reaction in individuals with a crustacean allergy (Kamemura et al. 2018). Occupational exposures leading to allergies also pose a threat to people who work closely with edible insects (Mlcek et al. 2014). Double-blind and placebo controlled trials, food challenges, and research on molecular mechanisms are needed to confirm and further explore this topic.

Ambiguities about the health impacts of entomophagy also exist and warrant investigation. As food, insects primarily impact health by providing nutrients. Available data on the nutrient content of edible insects are extensive, but published studies use inconsistent methodologies, utilize insects from disparate sources and reared under variable conditions, and sometimes evaluate insects in different life stages. More rigorous analyses are needed, including assessments of insect nutrients not thoroughly investigated (particularly vitamins), nutrient bioavailability, as well as the presence of non-nutrients, and anti-nutrients in various species or products.

Micronutrient bioavailability from consumed insects is not well understood. Iron is of particular relevance to global health, and unlike the iron in vertebrates, insect iron is primarily present as non-heme ferritin and holoferritin (Mwangi et al. 2018). One recent study measured the in vitro iron bioavailability from four insects and compared it to sirloin beef and whole wheat flour using simulated digestion (Latunde-Dada et al. 2016). Iron solubility for insects was greater than steak or whole wheat flour, but that insect iron bioavailability varied significantly by species. More data are needed to understand bioavailability and bio-accessibility of all insect micronutrients.

Insects contain relevant levels of dietary fiber, a non-nutrient. The fate of insect chitin in the human gastrointestinal tract is not fully understood, but evidence suggests that at least some humans have gastric chitinases capable of degrading chitin (Paoletti et al. 2007). Through digestion, deacetylation, and hydrolysis, it is plausible that insect chitin derivatives (e.g., chitosan or chitooligosaccharides) could function as prebiotics, promoting the growth of commensal bacteria. More research is needed to understand this mechanism and determine how chitin in insects or isolated chitin could impact consumer health.

Anti-nutrients, such as phytic acids, may impact the bioavailability of nutrients in insects, particularly minerals, acting as chelators that bind micronutrients and inhibit their absorption. Anti-nutrients have been documented in several edible insects (Omotoso 2006; Chakravorty et al. 2016), but many species have not yet been analyzed. It should be noted that heating and processing may impact anti-nutrient concentration, nutrient digestibility (El Hassan et al. 2008), and vitamins that are not heat stable (Williams et al. 2016).

Very few studies have measured direct health impacts of insect consumption. One recent clinical trial explored the influence of edible cricket powder on gut microbiota in healthy adults (Stull et al. 2018a). Another study assessed the impact of insect protein supplementation on changes in muscle mass and strength during resistance training (Vangsoe et al. 2018). However, these limited investigations leave ample room for more research on direct health outcomes from entomophagy via clinical trials and longitudinal studies, which will be crucial to building evidence regarding the health benefits and risks from insect consumption in the short and long-term. Similarly, identifying specific allergens in insects via gene sequencing will help to provide appropriate warning labels on commercial insect foods and general public health information to small-scale collectors and producers.

Research recommendation 3: public and consumer acceptance

Social research on consumer perceptions will be necessary if edible insects are to enter the mainstream in cultures that do not traditionally engage in entomophagy and in settings where eating farmed insects (as opposed to wild-collected insects) is novel. Eating insects involves a series of decisions strongly influenced by consumer knowledge, exposure to insects as food, and socio-cultural perceptions (Tan et al. 2015; Stull et al. 2018b; Piha et al. 2018). Cultural experience is instrumental in driving the acceptability all food, and even in contexts, where some insects are eaten, there is wide variability by tribe or population in terms of what specific insects are considered food (Ghosh et al. 2018).

Cultural attitudes towards edible insects in Europe and North America are often associated with aversion and likened to disgust (Looy et al. 2014; La Barbera et al. 2018). Clearly, the adoption of new foods comes with challenges, but altering cultural tastes is not insurmountable; the eruption of sushi's popularity in just 10 years is one example of a rapid cultural shift without any concentrated policy efforts (Johnson 2010). The popularity of formerly abstruse but now fashionable foods such as kombucha, goji berries, soy milk, and quinoa also exemplify how virtually unknown foods can easily gain notoriety (Shelomi 2015), especially with targeted messaging. In other contexts, socio-cultural

acceptance of new foods often depends on consumer marketing or endorsements from governments and local leaders who will confirm that the food is appropriate and in alignment with local foodculture. Promoting entomophagy through minilivestock farming will be no different—acceptance of new insect foods will necessitate strategic educational campaigns hinged on a comprehensive understanding of how people perceive insect foods and what elements or practices are essential for consumer comfort/motivation. Transdisciplinary research is needed to add depth to current understandings of what drives the rejection or acceptance of insects as food in variable contexts (Ghosh et al. 2018).

Research recommendation 4: ethics and social justice

There is limited research on ethical considerations for entomophagy and minilivestock farming. Questions regarding the sentience of insects remain, and protocols to avoid inflicting unnecessary distress or pain have not been formalized. More research on animal welfare throughout insect farming and harvesting is needed (Pali-Schöll et al. 2018). Other ethical challenges may stem from social relationships and biological webs—specifically the wellbeing of farmers and consumers, as well as the welfare of ecosystems (Waltner-Toews and Houle 2017). As a new edible insects industry emerges, there is a need for mindful planning: how should this industry evolve? Moreover, attention to farm worker rights, power dynamics, and the desires of communities who eat or produce insects themselves is needed—extending beyond the realm of productivity science. If production scales-up with a focus on technical aspects of farming but without attention to structural inequalities that dictate who controls and benefits from edible insects, the growing edible insect industry could reinforce existing power relations; hence, more ‘power-aware’ approaches to research and trade that include marginalized participants in decision making could help promote a more democratic edible insects industry (Müller et al. 2016). Engaging producers, consumers, decision makers, and researchers from across disciplines will be essential to think through these issues.

Research recommendation 5: economic viability

Finally, the economics of insect cultivation need to be explored, including cost effectiveness, reliability, and quality on multiple scales. Export and import prices of edible insects may influence the viability of farming as a livelihood, and in certain contexts, such as Namibia and Thailand, the market is favorable for sellers (Dobermann et al. 2017). Currently, most insect production systems are labor intensive. In Western countries, this leads to a high-cost, high-end product. Mechanization techniques may yield a

more economically competitive industry. In low-resource settings, extending shelf-life of locally produced insects and creating tools that allow insects to be farmed in bulk will improve their market value. With growing awareness of the nutritional and environmental benefits of edible insects, consumer demand may rise, and the commercial edible insect sector is already developing methods permissive for large-scale rearing (Ghosh et al. 2018). Market and value chain research across the globe is needed to fully understand the scale, scope, and potential of different types of edible insects as food.

The regulatory environment: ambiguity in US policy

The current lack of a cohesive legislative framework remains a primary impediment for the edible insects industry around the globe. Clear policies guiding the production and distribution of insect-based foods in the US are absent, which may impact development of edible insect products around the world given the outsized role the US plays in global food policy (Hawkes 2006). At the federal level, edible insects fall under the purview of the United States food and drug administration (FDA), while the United States department of agriculture (USDA) may be involved in oversight via their animal and plant health inspection service (APHIS) agency on a state-by-state basis. To date, however, the USDA has not yet expressed an interest in regulating insect agriculture.

Historically, the FDA has focused extensively on insects as a *defect* in human food, referring to them directly as ‘filth’ in the Compliance Policy Guides Sec. 555.600 (FDA 2015). Several FDA enforcement court cases have held that contaminating filth includes insect fragments or the presence of insects in a food facility (Boyd 2017). Similarly, current good manufacturing practice (cGMP) regulations stipulate that food manufacturers must limit the presence of ‘pests’ on the premises, including insects (CFR 2017) and control for insect parts in food (allowable only at certain levels) (FDA 2011). Comparatively, the FDA has given very little official attention to insects themselves as *food*.

Informally, insects have been recognized as food by regulators in select cases. The FDA has stated in non-binding correspondence with producers that there is no specific regulation that condones or prohibits the use of insects as food; rather, insects are considered food, like all foods, only if consumption is their “intended use” under Sec. 201(f) of the FDCA. Furthermore, unofficial guidance requires that food insects be clean (i.e., free from toxins, filth, and pathogens), packaged, properly labeled with scientific names, reared specifically for human consumption using cGMP, and not caught from the wild.

Despite the casual advice provided in these communications, the FDA has not yet formally distinguished edible

‘food’ insects from those that are considered ‘filth’ under the FDCA (Boyd 2017). The regulatory status of edible insects remains ambiguous, evidenced by examples of FDCA violations, such as the one handed down for misbranding of a candy containing mealworms (Messa 1993), and express permissions, such as those give for use of confectioners glaze (shellac) and carmine dye derived from cochineal insects (*Dactylopius coccus*) as long as they are declared on all food labels [21 CFR 73.100 (d)(2)].

The regulatory environment: policy progress and gaps in Europe

The European Union (EU) has made some recent advances in this policy space. Until recently, there was legal uncertainty regarding the regulatory classification of edible insects and patchwork regulatory enforcement dictated insect sales country-by-country. For example, the old Novel Food Regulation (258/1997/EC) posed a challenge for integrating edible insects into the European market, as food ingredients and foods not consumed in significant amounts by people in the EU before May 15, 1997, were considered ‘novel.’ This designation included food ingredients isolated from animals and did not specify whole insects versus insect parts. Several EU member states interpreted this regulation differently and retained variable, individualized classifications for insects. Italy, for example, viewed whole insects and their component parts as novel. Belgium and the Netherlands conversely considered only isolated substances from insects (e.g., proteins, lipids) novel. This led to fragmentation in the insect market, as inconsistent novel classifications made insects subject to differing degrees of pre-market screening and authorization across Europe.

The new comprehensive regulation on Novel Foods (EU 2015/2283) enacted in January 2018 has clarified this issue to some extent and harmonized standards across the EU. It expands categories of novel foods to include whole edible insects, insect parts, and other foods not produced or used before 1997 (European Parliament 2018). Under these new parameters, edible insects and their parts can be placed on the EU market provided that the “authorized conditions of use, labeling requirements, and specifications are respected” (European Commission 2018). A simplified and centralized authorization protocol has been developed to expedite authorization.

The European Food Safety Authority (EFSA) will evaluate the safety of novel foods, including novel foods that are traditionally consumed in countries outside the EU. If safety can be “established on the basis of evidence of a history of consumption in the third country, and there are no safety concerns raised by EU member states or EFSA, the traditional food will be allowed to be placed on the EU market” (European Commission 2018). Industry leaders are hopeful

that the revised policy will launch both imported and domestically produced edible insects on to more European plates.

In terms of managing safe insect production, the EU is also leading the charge with organizations galvanizing to generate comprehensive guidelines for edible insect producers and retailers. In February 2019, the not-for-profit organization the International Platform of Insects for Food and Feed (IPIFF) published a guidance document on best practice for quality assurance and hygienic insect production for businesses producing, processing, and marketing insects safe for human consumption and animal feed (IPFF 2019). The non-binding document aligns with EU regulations (EC No 1831/2003 and 853/2004) related to food and feed safety and integrity. It covers production steps including insect feeding, breeding, harvesting, processing, storage, transport, and retail activities. Moreover, the guide highlights crucial safety procedures for insect production as were previously determined by the EFSA. While the guide has not yet been recognized by European institutions, IPFF shared the document in accordance with EU procedures with the European Commission services after it was assessed by the Standing Committee on Plants, Animals, Food and Feed (IPFF 2019). A similar document for the US does not yet exist.

Impacts of current regulations

In the US, the dearth of direct guidance documents from the FDA leaves researchers, producers, and retailers uninformed. While food companies are advised to follow current cGMP, insect farmers must rely on their own common sense to assess quality in production. Retailers and restaurants interested in selling insect-based foods are often unsure about rules and oversight, adding to perceived risk. The absence of a stance from regulatory agencies could ultimately stifle the growth of the industry writ large (van Huis et al. 2013), and some argue that inaction on the part of the FDA is not a neutral position but rather a posture that discriminates against entomophagy (Boyd 2017). Failure to establish policies may bolster preponderate biases and cultural food norms that do not consider insects to be food (Gorham 1979), especially given the impact Western attitudes towards insects may have on global entomophagy trends (DeFoliart 1999).

Another regulatory setback is uncertainty regarding the generally regarded as safe (GRAS) designation for specific insect products (not including food additives). In the US, GRAS is often required by larger manufacturers and food retailers for new products. GRAS designation is obtained either via the scientific method (i.e., GRAS notification submission to the FDA), which is cumbersome and expensive, or the alternative 'self-affirmation' (self-GRAS determination) via record of use, which requires research on historical use of the product (CFR 2018). Self-GRAS determination allows producers to market their products immediately,

without having to wait for FDA to review and approve (Hutt et al. 2013). Self-designation is also less resource-intensive for the industry and the FDA. However, FDA-endorsed GRAS is desirable for some larger food retailers, and while money savings from self-determination may lower entry costs, they could subsequently result in later losses of approvals or reputational damage if mistakes are made. Both options remain a significant challenge for emerging insect entrepreneurs.

In the European context, entrepreneurs face a different set of hurdles. Although the revised novel foods guidelines are helpful for streamlining entry into EU markets broadly, they remain costly and time consuming. Like GRAS, novel foods regulation authorization may be laborious and time consuming for edible insect entrepreneurs, requiring pre-market approval for all insect-based foods. Details on the insect cultivation methods may also be necessary to include in applications for authorization, as they can impact safety. Risk assessment is a required element for approval of novel foods in Europe and GRAS designation in the US; thus, extensive food safety research as part of the regulatory process will help guarantee the safety of edible insect products in the future and propel the industry forward.

Policy recommendations and emerging efforts to shape Policy

The US has an opportunity to join Europe as a leader in insect production and dissemination, but the policy environment must evolve in tandem with increased research. There are at least four initial policy-related changes that could prop up the edible insects industry in the US. First, legal recognition by the FDA that many insects are in fact food would help the industry overcome current stigma. This might require an amendment to the FDCA, and potentially the development of a specific test to differentiate insects that are 'filth' from insects that are 'food' (Boyd 2017). Moreover, a clear definition distinguishing between 'food' and 'filth' insects could also clarify when or if a physical test is needed. Second, it would be helpful for the FDA to provide clear instruction as to the GRAS process, specifically for insect-derived food ingredients. Most helpful would be guidance on specific relevant toxicology or nutritional evaluations for insects, when they are needed, and how to form and use an expert panel to complete the GRAS dossier. Third, given the extensive historical and modern consumption of insects across the globe, as well as the regulatory precedent for acceptable levels of insect parts in human food, it would be prudent for the FDA to create an expedited GRAS process or category for insect-based food ingredients. Finally, members of the edible insect industry should collaborate and advocate their own working definitions of insects as food and work to develop food safety and production standards that can collectively be presented

to the FDA. This may improve transparency and safety in the industry, while giving the FDA a framework they can more easily assess, approve, and enforce.

In the EU and elsewhere, there is a need for policies that support development of efficient and safe minilivestock farming mechanisms, so as to reach those who would most benefit from increased access to edible insects. Well-established, axiomatic protocols for small-scale insect production are scarce. A concentrated effort by donor agencies such as the German Corporation for International Cooperation (GIZ) or the United States Agency for International Development (USAID) could spur global movement on applied research and program investment. Likewise, partnerships between affiliated institutions, other non-governmental organizations, and governments could drive a comprehensive and well-informed movement towards enhanced insect production that supplies sought-after nutrients to food insecure populations. Integrating minilivestock with other nutrition sensitive and nutrition specific agriculture projects, such as those included in the US government's *Feed the Future* initiative, would be timely and impactful. Both funding and regulatory support for minilivestock could target specific vulnerable groups, to support nutrition, agriculture, and livelihoods.

Several organizations have emerged in response to the lack of regulatory guidelines, including: IPIFF, the North American Coalition for Insect Agriculture (NACIA), the Woven Network, and the Tripartite Organization for the Promotion of Insect Consumption (TOPIC) (Mason et al. 2018). Each group has a unique strategy for advocating for the removal of regulatory roadblocks, collaborating across stakeholders groups, and fostering growth of the edible insects industry. The cooperation and leadership by these organizations is essential to jumpstart scalable and substantive initiatives to expand consumption of potentially safe, nutritious, and sustainable insects and insect-based foods.

Conclusions and a way forward

The next steps to capitalize on the benefits of edible insects are as follows: (1) generate and galvanize knowledge sharing networks at the nexus of minilivestock stakeholders including producers, academic institutions, governments, and international agencies; (2) invest in research including controlled laboratory studies, practical and contextual analyses, life cycle and environmental assessments, clinical trials, epidemiologic studies, ethical analyses, and investigations of consumer perceptions; and (3) advocate for policies to support emerging edible insect entrepreneurs around the globe, recognize insects as food, and set clear regulatory guidelines for insect production and sales.

Edible insects represent an underdeveloped, under-researched, and under-utilized food and feed source. Both research and policy action are essential to fully explore opportunities for insects to provide dual benefits to human nutrition and environmental protection. Research on the safety and feasibility of insect agriculture will pave the way for new uses and streamlined production. Clear policies will also better capture the benefits of edible insects in places where they are already consumed, while also supporting the burgeoning trend in Western markets.

Acknowledgements Special thanks to Robert Nathan Allen, Kevin Bachhuber, Gabe Mott, Dr. Dean Stull, and Justin Butner who shared their industry insight with the authors. We also thank Dr. Maggie Grabow and Tobias Lunt for their editorial suggestions.

References

- Alexander P, Brown C, Arneth A et al (2017) Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Glob Food Secur* 15:22–32. <https://doi.org/10.1016/j.gfs.2017.04.001>
- Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. FAO, Rome
- Belluco S, Losasso C, Maggioletti M et al (2013) Edible insects in a food safety and nutritional perspective: a critical review. *Compr Rev Food Sci Food Saf* 12:296–313. <https://doi.org/10.1111/1541-4337.12014>
- Bodenheimer FS (1951) Insects as human food: a chapter of the ecology of man. W. Junk, The Hague
- Boyd MC (2017) Cricket soup: a critical examination of the regulation of insects as food. *Yale Law Policy Rev* 36(1):17
- Broekman H, Knulst A, Den Hartog Jager S et al (2015) Shrimp allergic patients are at risk when eating mealworm proteins. *Clin Transl Allergy* 5:P77. <https://doi.org/10.1186/2045-7022-5-S3-P77>
- Bukkens S (2005) Insects in the human diet. In: Paoletti MG (ed) Ecological implications of minilivestock. Potential of insects, rodents, frogs and snails. Science Enfield, NH, pp 545–577
- CFR (2017) Current Good Manufacturing Practice in Manufacturing, Packing, or Holding Human Food, Code of Federal Regulation Title 21 Sec. 110.3(j). <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=110>
- CFR (2018) Eligibility for classification as generally recognized as safe (GRAS). Code of Federal Regulation Title 21 Section 170.3. <https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfCFR/CFRSearch.cfm?fr=170.30>
- Chakravorty J, Ghosh S, Megu K et al (2016) Nutritional and anti-nutritional composition of *Oecophylla smaragdina* (Hymenoptera: formicidae) and *Odontotermes* sp. (Isoptera: termitidae): Two preferred edible insects of Arunachal Pradesh, India. *J Asia-Pac Entomol* 19:711–720. <https://doi.org/10.1016/j.aspen.2016.07.001>
- Christensen DL, Orech FO, Mungai MN et al (2006) Entomophagy among the Luo of Kenya: a potential mineral source? *Int J Food Sci Nutr* 57:198–203
- Collavo A, Glew RH, Huang YS et al (2005) House cricket small-scale farming. In: Paoletti MG (ed) Ecological implications of minilivestock: potential of insects, rodents, frogs and snails. CRC Press, Enfield, pp 519–544

- DeFoliart GR (1995) Edible insects as minilivestock. *Biodivers Conserv* 4:306–321. <https://doi.org/10.1007/BF00055976>
- DeFoliart GR (1999) Insects as food: why the western attitude is important. *Annu Rev Entomol* 44:21
- Dobermann D, Swift JA, Field LM (2017) Opportunities and hurdles of edible insects for food and feed. *Nutr Bull* 42:293–308. <https://doi.org/10.1111/nbu.12291>
- EFSA Scientific Committee (2015) Risk profile related to production and consumption of insects as food and feed. *Eur Food Saf Auth J*. <https://doi.org/10.2903/j.efsa.2015.4257>
- El Hassan NM, Hamed SY, Hassan AB et al (2008) Nutritional evaluation and physicochemical properties of boiled and fried tree locust. *Pak J Nutr* 7:325–329. <https://doi.org/10.3923/pjn.2008.325.329>
- European Commission (2018) Legislation—food safety—European Commission. In: Food Saf./food/safety/novel_food/legislation_en. Accessed 27 Sep 2018
- European Parliament (2018) Regulation (EU) 2015/2283 of the European parliament and the council of 25 november 2015 on novel foods, amending regulation (EU) No 1169/2011 of the European Parliament and of the Council and Repealing Regulation (EC) No 258/97 of the European Parliament and of the Council and Commission Regulation (EC) No 1852/2001
- FAO, IFAD, UNICEF et al (2018) The state of food security and nutrition in the world. Building climate resilience for food security and nutrition. Food and Agriculture Organization of the United Nations, Rome
- Farvid MS, Eliassen AH, Cho E et al (2016) Dietary fiber intake in young adults and breast cancer risk. *Pediatrics* 137(3):e20151226. <https://doi.org/10.1542/peds.2015-1226>
- FDA (2011) Defects level handbook. Washington, D.C. <https://www.fda.gov/food/ingredients-additives-gras-packaging-guidance-documents-regulatory-information/food-defect-levelshandbook>
- FDA (2015) FDA compliance policy guide. Food and Drug Administration, US
- Finke MD (2002) Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biol* 21:269–285. <https://doi.org/10.1002/zoo.10031>
- Finke MD (2007) Estimate of chitin in raw whole insects. *Zoo Biol* 26:105–115. <https://doi.org/10.1002/zoo.20123>
- Gerber PJ, Steinfeld H, Henderson B et al (2013) Tackling climate change through livestock—A global assessment of emissions and mitigation opportunities. Food and agriculture organization of the United Nations, Rome
- Ghosh S, Jung C, Meyer-Rochow VB (2018) What governs selection and acceptance of edible insect species? In: Halloran A, Flore R, Vantomme P, Roos N (eds) *Edible insects in sustainable food systems*. Springer, Cham
- Gorham JR (1979) The significance for human health of insects in food. *Annu Rev Entomol* 24:209–224. <https://doi.org/10.1146/annurev.en.24.010179.001233>
- Grabowski NTh, Klein G (2017) Bacteria encountered in raw insect, spider, scorpion, and centipede taxa including edible species, and their significance from the food hygiene point of view. *Trends Food Sci Technol* 63:80–90. <https://doi.org/10.1016/j.tifs.2017.01.007>
- Gustavsson J, Sonesson U (2011) Global food losses and food waste: extent, causes, and prevention. Food and Agriculture Organization of the United Nations, Rome
- Hahn T, Roth A, Febel E et al (2018) New methods for high-accuracy insect chitin measurement. *J Sci Food Agric* 98:5069–5073. <https://doi.org/10.1002/jsfa.9044>
- Hall FG, Jones OG, O'Haire ME, Liceaga AM (2017) Functional properties of tropical banded cricket (*Gryllodes sigillatus*) protein hydrolysates. *Food Chem* 224:414–422. <https://doi.org/10.1016/j.foodchem.2016.11.138>
- Halloran A, Vantomme P, Hanboonsong Y, Ekesi S (2015) Regulating edible insects: the challenge of addressing food security, nature conservation, and the erosion of traditional food culture. *Food Secur* 7:739–746. <https://doi.org/10.1007/s12571-015-0463-8>
- Hanboonsong Y, Jamjanya T, Durst PB (2013) Six legged livestock: edible insect farming collecting and marketing in Thailand. Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific, Bangkok
- Hawkes C (2006) Uneven dietary development: linking the policies and processes of globalization with the nutrition transition, obesity and diet-related chronic diseases. *Glob Health* 2:4. <https://doi.org/10.1186/1744-8603-2-4>
- Hedenus F, Wirsenius S, Johansson DJA (2014) The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Clim Change* 124:79–91. <https://doi.org/10.1007/s10584-014-1104-5>
- Hong HA, To E, Fakhry S et al (2009) Defining the natural habitat of *Bacillus* spore-formers. *Res Microbiol* 160:375–379. <https://doi.org/10.1016/j.resmic.2009.06.006>
- Hutt P, Merrill R, Grossman L (2013) Food and drug law, 4th edn. Foundation Press, St. Paul
- Illgner P, Nel E (2000) The geography of edible insects in sub-saharan africa: a study of the mopane caterpillar. *Geogr J* 166:336–351. <https://doi.org/10.1111/j.1475-4959.2000.tb00035.x>
- IPIFF (2019) IPIFF guide on good hygiene practices for European Union (EU) producers of insects as food and feed. IPIFF General Assembly, Brussels, Belgium
- Johnson DV (2010) The contribution of edible forest insects to human nutrition and to forest management. In: Durst PB, Johnson DV, Leslie RN, Shono K (eds) *Forest insects as food: humans bite back*. Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific, Bangkok
- Jongema Y (2014) List of edible insects of the world (April 1, 2014). In: Wageningen. UR. <http://www.wageningenur.nl/en/Expertise-Services/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm>. Accessed 13 Dec 2014
- Jongema Y (2017) List of edible insects of the world. In: List edible insects world April 1 2017. <http://www.wageningenur.nl/en/Expertise-Services/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm>. Accessed 18 Sep 2018
- Kamemura N, Sugimoto M, Tamehiro N et al (2018) Cross-allergenicity of crustacean and the edible insect *Gryllus bimaculatus* in patients with shrimp allergy. *Mol Immunol* 106:127–134. <https://doi.org/10.1016/j.molimm.2018.12.015>
- Klunder HC, Wolkers-Rooijackers J, Korpela JM, Nout MJR (2012) Microbiological aspects of processing and storage of edible insects. *Food Control* 26:628–631. <https://doi.org/10.1016/j.foodcont.2012.02.013>
- La Barbera F, Verneau F, Amato M, Grunert K (2018) Understanding Westerners' disgust for the eating of insects: the role of food neophobia and implicit associations. *Food Qual Prefer* 64:120–125. <https://doi.org/10.1016/j.foodqual.2017.10.002>
- Lapping K, Marsh DR, Rosenbaum J et al (2002) The positive deviance approach: challenges and opportunities for the future. *Food Nutr Bull* 23:128–135. <https://doi.org/10.1177/15648265020234S217>
- Latunde-Dada GO, Yang W, Vera Aviles M (2016) In vitro iron availability from insects and sirloin beef. *J Agric Food Chem* 64:8420–8424. <https://doi.org/10.1021/acs.jafc.6b03286>
- Looy H, Dunkel FV, Wood JR (2014) How then shall we eat? Insect-eating attitudes and sustainable foodways. *Agric Hum Values* 31:131–141
- Lundy ME, Parrella MP (2015) Crickets are not a free lunch: protein capture from scalable organic side-streams via high-density

- populations of *Acheta domesticus*. PLoS One 10:e0118785. <https://doi.org/10.1371/journal.pone.0118785>
- Manditsera FA, Luning PA, Fogliano V, Lakemond CMM (2019) The contribution of wild harvested edible insects (Eulepida mashona and Henicus whellani) to nutrition security in Zimbabwe. J Food Compos Anal 75:17–25. <https://doi.org/10.1016/j.jfca.2018.09.013>
- Marshall DL, Dickson JS, Nguyen NH (2016) Chapter 8—Ensuring food safety in insect based foods: mitigating microbiological and other foodborne hazards. In: Dossey AT, Morales-Ramos JA, Rojas MG (eds) Insects as sustainable food ingredients. Academic Press, San Diego, pp 223–253
- Martínez I, Lattimer JM, Hubach KL et al (2013) Gut microbiome composition is linked to whole grain-induced immunological improvements. ISME J 7:269–280. <https://doi.org/10.1038/ismej.2012.104>
- Mason JB, Black R, Booth SL et al (2018) Fostering strategies to expand the consumption of edible insects: the value of a tripartite coalition between academia, industry, and Government. Curr Dev Nutr. <https://doi.org/10.1093/cdn/nzy056>
- McKeown NM, Meigs JB, Liu S et al (2004) Carbohydrate nutrition, insulin resistance, and the prevalence of the metabolic syndrome in the Framingham Offspring Cohort. Diabetes Care 27:538–546
- Melo V, Garcia M, Sandoval H et al (2011) Quality proteins from edible indigenous insect food of Latin America and Asia. Emir J Food Agric 23:283–289
- Messa EC (1993) S.S. Lollipop, Warning Letter WL-56-3
- Meyer-Rochow VB (1975) Can insects help to ease the problem of world food shortage? Search 6:261–262
- Meyer-Rochow VB (2010) Entomophagy and its impact on world cultures: the need for a multidisciplinary approach. In: Forest insects as food: humans bite back. Proceedings of a workshop on Asia-Pacific resources and their potential for development. Food and agriculture organization of the united nations regional office for Asia and the Pacific, Bangkok, pp 23–36
- Mlcek J, Rop O, Borkovcova M, Bednarova M (2014) A comprehensive look at the possibilities of edible insects as food in europe—a review. Pol J Food Nutr Sci 64:147–157
- Müller A, Evans J, Payne CLR, Roberts R (2016) Entomophagy and power. J Insects Food Feed 2:121–136. <https://doi.org/10.3920/JIFF2016.0010>
- Mwangi MN, Oonincx DGAB, Stouten T et al (2018) Insects as sources of iron and zinc in human nutrition. Nutr Res Rev. <https://doi.org/10.1017/s0954422418000094>
- Nadeau L, Nadeau I, Franklin F, Dunkel F (2015) The potential for entomophagy to address undernutrition. Ecol Food Nutr 54:200–208. <https://doi.org/10.1080/03670244.2014.930032>
- Nowak V, Persijn D, Rittenschober D, Charrondiere UR (2014) Review of food composition data for edible insects. Food Chem. <https://doi.org/10.1016/j.foodchem.2014.10.114>
- Omotoso OT (2006) Nutritional quality, functional properties and anti-nutrient compositions of the larva of *Cirina forda* (Westwood) (Lepidoptera: saturniidae). J Zhejiang Univ Sci B 7:51–55. <https://doi.org/10.1631/jzus.2006.B0051>
- Oonincx DGAB, de Boer IJM (2012) Environmental impact of the production of mealworms as a protein source for humans—a life cycle assessment. PLoS One. <https://doi.org/10.1371/journal.pone.0051145>
- Oonincx DGAB, van der Poel AFB (2011) Effects of diet on the chemical composition of migratory locusts (*Locusta migratoria*). Zoo Biol 30:9–16. <https://doi.org/10.1002/zoo.20308>
- Oonincx DGAB, van Isterbeeck J, Heetkamp MJW et al (2010) An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLoS One 5:1–7. <https://doi.org/10.1371/journal.pone.0014445>
- Pali-Schöll I, Binder R, Polesny F, Monsó S (2018) Edible insects—defining knowledge gaps in biological and ethical considerations of entomophagy. Crit Rev Food Sci Nutr. <https://doi.org/10.1080/10408398.2018.1468731>
- Paoletti MG, Norberto L, Damini R, Musumeci S (2007) Human gastric juice contains chitinase that can degrade chitin. Ann Nutr Metab 51:244–251. <https://doi.org/10.1159/000104144>
- Paul A, Frederick M, Megido RC et al (2017) Insect fatty acids: a comparison of lipids from three orthopterans and *Tenebrio molitor* L. larvae. J Asia-Pac Entomol 20:337–340. <https://doi.org/10.1016/j.aspen.2017.02.001>
- Payne CLR, Scarborough P, Rayner M, Nonaka K (2015) Are edible insects more or less ‘healthy’ than commonly consumed meats? A comparison using two nutrient profiling models developed to combat over- and undernutrition. Eur J Clin Nutr. <https://doi.org/10.1038/ejcn.2015.149>
- Payne CLR, Scarborough P, Rayner M, Nonaka K (2016) A systematic review of nutrient composition data available for twelve commercially available edible insects, and comparison with reference values. Trends Food Sci Technol 47:69–77. <https://doi.org/10.1016/j.tifs.2015.10.012>
- Pereira MA, O’Reilly E, Augustsson K et al (2004) Dietary fiber and risk of coronary heart disease: a pooled analysis of cohort studies. Arch Intern Med 164:370–376. <https://doi.org/10.1001/archinte.164.4.370>
- Piha S, Pohjanheimo T, Lähteenmäki-Uutela A et al (2018) The effects of consumer knowledge on the willingness to buy insect food: an exploratory cross-regional study in Northern and Central Europe. Food Qual Prefer 70:1–10. <https://doi.org/10.1016/j.foodqual.2016.12.006>
- Premalatha M, Abbasi T, Abbasi T, Abbasi SA (2011) Energy-efficient food production to reduce global warming and ecodegradation: the use of edible insects. Renew Sustain Energy Rev 15:4357–4360. <https://doi.org/10.1016/j.rser.2011.07.115>
- Ramos-Elorduy J (2006) Threatened edible insects in Hidalgo, Mexico and some measures to preserve them. J Ethnobiol Ethnomed 2:51. <https://doi.org/10.1186/1746-4269-2-51>
- Ranganathan J, Vennard D, White R, Lipinski B, Searchinger T, Dumas P, Forslund A, Guyomard H, Manceron S, Marajo-Petit-zon E, Le Mouél C, Havlik P, Herrero M, Zhang X, Wirsén S, Ramos F, Yan X, Phillips M, Mungkung R (2016) Shifting diets for a sustainable food future. World Resources Institute Working Paper. <https://www.wri.org/publication/shifting-diets>
- Ribeiro JC, Cunha LM, Sousa-Pinto B, Fonseca J (2018) Allergic risks of consuming edible insects: A systematic review. Mol Nutr Food Res 62:10. <https://doi.org/10.1002/mnfr.201700030>
- Roberts C (1998) Long-term costs of the mopane worm harvest. Oryx 32:6–8. <https://doi.org/10.1046/j.1365-3008.1998.00006.x>
- Rumpold BA, Schlüter OK (2013) Nutritional composition and safety aspects of edible insects. Mol Nutr Food Res 57:802–823. <https://doi.org/10.1002/mnfr.201200735>
- Schabel HG (2010) Forest insects as food: a global review. Food and Agriculture Organization of the United Nations (FAO), Rome, pp 37–64
- Shelomi M (2015) Why we still don’t eat insects: assessing entomophagy promotion through a diffusion of innovations framework. Trends Food Sci Technol 45:311–318. <https://doi.org/10.1016/j.tifs.2015.06.008>
- Stull VJ, Finer E, Bergmans RS et al (2018a) Impact of edible cricket consumption on gut microbiota in healthy adults, a double-blind, randomized crossover trial. Sci Rep 8:10762. <https://doi.org/10.1038/s41598-018-29032-2>
- Stull VJ, Wamulume M, Mwalukanga MI et al (2018b) “We like insects here”: entomophagy and society in a Zambian village. Agric Hum Values. <https://doi.org/10.1007/s10460-018-9878-0>

- Tan HSG, Fischer ARH, Tinchin P et al (2015) Insects as food: exploring cultural exposure and individual experience as determinants of acceptance. *Food Qual Prefer* 42:78–89. <https://doi.org/10.1016/j.foodqual.2015.01.013>
- Tap J, Furet J-P, Bensaada M et al (2015) Gut microbiota richness promotes its stability upon increased dietary fibre intake in healthy adults. *Environ Microbiol* 17:4954–4964. <https://doi.org/10.1111/1462-2920.13006>
- Ter Beek A, Brul S (2010) To kill or not to kill Bacilli: opportunities for food biotechnology. *Curr Opin Biotechnol* 21:168–174. <https://doi.org/10.1016/j.copbio.2010.03.014>
- Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108:20260–20264. <https://doi.org/10.1073/pnas.1116437108>
- UNDESA (2017) World population projected to reach 9.8 billion by 2050. In: UN. Dep. Econ Soc Aff. <https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html>. Accessed 9 Jan 2019
- USDA (2018) National nutrient database for standard reference 1 release April, 2018. In: U. S. Dep. Agric. Agric. Res. Serv. Nutrient Data Laboratory Home Page, <http://www.ars.usda.gov/ba/bhnrc/ndl>
- van Huis A (2013) Potential of insects as food and feed in assuring food security. *Annu Rev Entomol* 58:563–583. <https://doi.org/10.1146/annurev-ento-120811-153704>
- van Huis A, Van Itterbeeck J, Klunder H, et al (2013) Edible insects: Future prospects for food and feed security. Food and Agriculture Organization of the United Nations (FAO), Rome
- Vandeweyer D, Crauwels S, Lievens B, Van Campenhout L (2017) Microbial counts of mealworm larvae (*Tenebrio molitor*) and crickets (*Acheta domesticus* and *Gryllobates sigillatus*) from different rearing companies and different production batches. *Int J Food Microbiol* 242:13–18. <https://doi.org/10.1016/j.ijfoodmicro.2016.11.007>
- Vandeweyer D, Wynants E, Crauwels S et al (2018) Microbial dynamics during industrial rearing, processing, and storage of tropical house crickets (*Gryllobates sigillatus*) for human consumption. *Appl Env Microbiol* 84:e00255-18. <https://doi.org/10.1128/AEM.00255-18>
- Vangsoe MT, Joergensen MS, Heckmann L-HL, Hansen M (2018) Effects of insect protein supplementation during resistance training on changes in muscle mass and strength in young men. *Nutrients* 10. <https://doi.org/10.3390/nu10030335>
- Verhoeckx KCM, van Broekhoven S, den Hartog-Jager CF et al (2014) House dust mite (Der p 10) and crustacean allergic patients may react to food containing yellow mealworm proteins. *Food Chem Toxicol* 65:364–373. <https://doi.org/10.1016/j.fct.2013.12.049>
- Verkerk MC, Tramper J, van Trijp JCM, Martens DE (2007) Insect cells for human food. *Biotechnol Adv* 25:198–202. <https://doi.org/10.1016/j.biotechadv.2006.11.004>
- Waltner-Toews D, Houle K (2017) Biophilia on the dinner plate: a conversation about ethics and entomophagy. *Food Ethics* 1:157–171. <https://doi.org/10.1007/s41055-017-0015-3>
- Williams JP, Williams JR, Kirabo A et al (2016) Chapter 3—nutrient content and health benefits of insects. In: Dossey AT, Morales-Ramos JA, Rojas MG (eds) *Insects as sustainable food ingredients*. Academic Press, San Diego, pp 61–84
- Wittman AM, Akkerdaas JH, van Leeuwen J et al (1994) Identification of a cross-reactive allergen (presumably tropomyosin) in shrimp, mite and insects. *Int Arch Allergy Immunol* 105:56–61. <https://doi.org/10.1159/000236803>
- Womeni HM, Linder M, Tiencheu B et al (2009) Oils of insects and larvae consumed in Africa: potential sources of polyunsaturated fatty acids. *Ol Corps Gras, Lipides* 16:230–235. <https://doi.org/10.1051/ocl.2009.0279>
- Yen AL (2008) Entomophagy and insect conservation: some thoughts for digestion. *J Insect Conserv* 13:667. <https://doi.org/10.1007/s10841-008-9208-8>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.