frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 11 November 2022
DOI 10.3389/fsufs.2022.1021861

Check for updates

OPEN ACCESS

EDITED BY
Rob Morrison,
Agricultural Research Service (USDA),
United States

REVIEWED BY
Carlos Henrique Marchiori,
Goiano Federal Institute
(IFGOIANO), Brazil
Mandeep Rathee,
Chaudhary Charan Singh Haryana
Agricultural University, India

*CORRESPONDENCE
G. Melgar-Lalanne
gmelgar@uv.mx

SPECIALTY SECTION
This article was submitted to
Crop Biology and Sustainability,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 17 August 2022
ACCEPTED 21 October 2022
PUBLISHED 11 November 2022

CITATION
Piña-Domínguez IA, Ruiz-May E, Hernández-Rodríguez D, Zepeda RC and Melgar-Lalanne G (2022) Environmental effects of harvesting some Mexican wild edible insects: An overview.
Front. Sustain. Food Syst. 6:1021861.
doi: 10.3389/fsufs.2022.1021861

Environmental effects of harvesting some Mexican wild edible insects: An overview

I. A. Piña-Domínguez[1], E. Ruiz-May[2], D. Hernández-Rodríguez[3], R. C. Zepeda[4] and G. Melgar-Lalanne[3]*

[1]Doctorado en Ciencias Biomédicas, Centro de Investigaciones Biomédicas, Universidad Veracruzana, Xalapa, Mexico, [2]Red de Estudios Moleculares Avanzados, Clúster Científico y Tecnológico BioMimic®, El Instituto de Ecología, Xalapa, Mexico, [3]Instituto de Ciencias Básicas, Universidad Veracruzana, Xalapa, Mexico, [4]Laboratorio de Biomedicina Integral y Salud, Centro de Investigaciones Biomédicas, Universidad Veracruzana, Xalapa, Mexico

Most traditional edible insects are collected from the forest and agricultural fields, where they are considered pests. However, their importance goes beyond this. They also have an ecological role and potential to be an emerging alternative source of high-quality nutrients that can help satisfy the growing food demand for the human population. Agricultural insect pests are a healthy food source during the harvesting season in many tropical countries. In Mexico, wild insects such as *chicatana* (queen of flying leaf-cutter ant, *Atta mexicana* Smith, 1,858; Hymenoptera: Formicidae), *chapulín* (grasshopper, *Pyrgomorphidae*), *chinicuil* (agave red worm, *Comadia redtenbacheri* Hammerschmidt, 1,848: Lepidoptera, Cossidae), and *meocuil* (agave white worm, *Aegiale hesperiaris* Walker 1,856, Lepidoptera, Hesperiidae) are seasonally collected from the agricultural land and forest for food and medicine. Thus, their consumption might be regarded as support for biological plague control. However, in most countries (Mexico included), there is a lack of legislation about edible insects from harvesting to sacrifice and even their main safety aspects. So then, this research aims to provide an updated assessment of the potential use of agricultural pest insects as a sustainable alternative for food, considering current international legislative and ethical concerns about harvesting and consuming wild edible insects, focusing on some of the wild edible pest insects in Mexico.

KEYWORDS

edible insects, wild harvesting insects, agricultural pests, sustainability, sustainable food

Introduction

Insects contribute to the biodiversity and play an essential role in maintaining the ecosystem through their participation in seed dispersal, pollination, organic matter processing, water filtration, and other ecological services. These processes help to regulate plant diversity, photosynthesis, soil fertility, ecosystem structure, and water quality. Therefore, maintaining healthy insect communities is crucial for global sustainability and human development (Crespo-Pérez et al., 2020).

However, over the years, insect pests, principally species belonging to the orders Coleoptera and Lepidoptera, have represented significant economic losses. For example, a swarm of forty million desert locusts could eat 1 km^2 of farmland daily. Therefore, the stemborers, like desert locusts, may inflict the same damage. However, locusts destroy the entire yield of several farmers, while stemborers only reduce the profits of all farmers (FAO., 2021). That is why, as a control measure, industrial agriculture, even subsistence farming, uses pesticides to eliminate insects (Cerritos, 2008). However, beyond a solution, pesticides and insecticides have reduced insects, soil biota, and aquatic invertebrates' communities, negatively affecting the ecosystem (Pisa et al., 2021). However, the residues of pesticides present in edible insects when the pesticides are well-used did not cause human health problems (Murefu et al., 2019).

Approximately 92% of all edible insect species consumed are harvested directly from the environment (wild), 6% are semi-domesticated (semi-wild), and only 2% are bred in captivity (in-door farming) (Yen, 2015b). Therefore, sustainable wild harvesting of insects from the agricultural fields would contribute to their biological control (Cerritos and Klewer, 2015; Lesnik, 2017) and be advantageous for their use as food. However, it must be kept under strict control since overharvesting may negatively affect the biodiversity and abundance of insects (Pino-Moreno et al., 2020) and even put them at risk of extinction (Ramos-Elorduy, 2006).

Estimating the total number of food and medicinal insect species is rather vague based on existing literature. To date, the Jongema recompilation is the most accurate, with 2,111 edible species from all over the globe from the orders Coleoptera (beetles), Lepidoptera (butterflies), Hymenoptera (ants and bees), Orthoptera (grasshoppers), and Hemiptera (true bugs) (Jongema, 2020). However, some edible insects remain without a complete taxonomy identification (van Itterbeeck and Pelozuelo, 2022).

Insects have a high nutritional value because of the excellent protein range in the few characterized species, which varies from 7 to 70% on a dry matter basis (Jonas-Levi and Martinez, 2017). This high amount of proteins does that FAO has proposed insects as an alternative to fighting against malnutrition (FAO., 2021). Therefore, their use as food and feed ingredients has been gaining importance at the industrial level in the Western world (Melgar-Lalanne et al., 2019; Hernández-Álvarez et al., 2021). Finally, despite the growing interest in insect consumption, national legislation does not cover ethical aspects related to insect welfare during harvesting or the associated environmental impacts (Gjerris, 2015; Pali-Schöll et al., 2019). Thus, this review outlines some ecological aspects that should be considered in connection with the wild harvesting of edible insects, emphasizing the Mexican scenario.

Bibliographic search

For this review, the bibliographic search used the following databases: Scopus (www.scopus.com), Science Direct (https://www.sciencedirect.com/science), Scielo (https://scielo.org/es/), Dimensions (https://app.dimensions.ai/discover/publication) and Google scholar (https://scholar.google.com) during June 2021 to October 2022.

The articles were published from 1997 to 2022 in indexed scientific research, book scientific chapters and even in general journals when considered of interest.

The articles were written in English and Spanish.

The main terms used were: "edible insects," *chicatana* (*Atta mexicana*), *chapulín* (grasshopper, *Pyrgomorphidae*), *chinicuil* (*Comadia redtenbacheri*), and white maguey worm (*Aegiale hesperiaris*), "pest insects," "pesticides," "sustainable agriculture," "nutritional composition of insects" and "medicinal use of insects."

Insect plagues

Ecological impact of insects

Insect pests cause damage both in natural ecosystems and in systems managed by human being. The negative impact of pests on plants in natural habitats is not drastic and is naturally controlled by predators and parasitoids (Noble et al., 2019). On the other hand, in crops, insect pests represent a problem that can be serious or fatal due to their great capacity for expansion and rapid and proliferative reproduction because of the lack of natural depredators due to the use of industrial agriculture solutions such as the use of pesticides. Finally, in sustainable agriculture, the main objective of managing invasive insects as pests is not to eliminate the organisms that cause damage but to regulate the growth of populations to avoid the need for treatments or direct repression actions (Siviter et al., 2018). Based on this, it is necessary always to maintain a remnant of potential pest insects, to allow the survival and reproduction of their bioregulators (O'Neill et al., 2019). Furthermore, identifying the insects that cause the most significant economic damage to a crop allows for the appropriate management strategies (Wolff et al., 2017).

The use of pesticides is the leading way to control the presence of plagues. However, overuse has been widely explored from an environmental point of view, and the ecological damage is well documented. Pesticides have adverse impacts on water quality, plants and animals and are associated with adverse human health effects (Hough, 2021). Moreover, using chemical agents, such as conventional insecticides and fungicides, to control insect pests and disease-causing pathogens has several drawbacks, such as environmental disturbance, non-targeted effects, and economic expenses for the farmers (Balla et al., 2021). The resistance to different chemical pesticides by insects is another concern for industrial agriculture because of the consequences on the crops and the necessity to develop new pesticides (Hawkins et al., 2019). However, the impact of the use and abuse of pesticides on insect wellness has been less explored.

Other control practices include modifying the planting density, changing the soil preparation strategy, pruning to improve aeration irrigation, and strategically incorporating other plants, such as flowers and aromatic plants, into the productive environment (Edwards et al., 2017). Some cultural practices (pruning, and weed removal, among others) and an appropriate habitat manipulation might prevent the increase of pest populations already in the production environment and avoid the arrival of pests outside the area. When the population of invasive insects and pests increases, it is possible to apply preparations made from plants (nettle, paradise, tobacco, Indian Lilac, neem), crop residues (garlic, onion, green onion), household waste (ash from the stove), and animal waste (cow urine) to lower populations without causing damage to the ecosystem itself (Tomasetto et al., 2017). Insect harvesting of pest insects and their use as food can be a strategy with double benefits, allowing biological control of pests while generating a food source rich in protein that can meet the dietary demands of human populations. However, overharvesting may negatively affect the biodiversity and abundance of insects (Pino-Moreno et al., 2020) and even put them at risk of extinction (Ramos-Elorduy, 2006).

Ecological impacts of insect harvesting

About 40% of all wild insects are at risk of extinction (Sánchez-Bayo and Wyckhuys, 2019; Harvey et al., 2020a). The orders Lepidoptera, Hymenoptera, and Coleoptera are the most affected in terrestrial ecosystems. Some anthropogenic factors that have been identified as responsible for this situation are:

(1) loss of natural habitat due to deforestation and increased land used for agriculture and urban spaces.

(2) pollution caused by the massive use of chemical pesticides and fertilizers on agricultural land.

(3) biological factors, such as pathogens' presence, new species' introduction, and climate change (Sánchez-Bayo and Wyckhuys, 2019; Harvey et al., 2020b).

(4) overharvesting insects for culinary and medicinal purposes (Gahukar, 2020).

These factors are directly responsible for reducing invertebrates' abundance (like insects, arachnids, gastropods, and myriapods), diversity, and biomass across the biosphere (Harvey et al., 2020b). Furthermore, the decline of insects affects a wide range of ecosystem services, some of which are vital for food and feed production and security because invertebrates provide invaluable ecosystem services such as pollination, pest control and nutrient cycling (Hochkirch, 2016).

The overexploitation comes from the higher demand (Ramos-Elorduy, 2006; van Huis and Oonincx, 2017). For example, in Mexico, the state of Hidalgo (Ramos-Elorduy, 2006) has reported that the survival of edible insects inhabiting woodlands (edible forest insects) is threatened. Similarly, in Cameroon, Ngute et al. (2020) analyzed several species of caterpillars and found some effects of overexploitation on them. They found a reduction in the number of species and their abundance with the increase of vendors selling insects. Similar results, attributed to the increasing interest in insect consumption as food and their use for medicinal purposes, have been reported for species of Lepidoptera (Yen, 2015a). Wild insects are considered an essential source of animal protein in some communities; they are also valued in traditional medicine and provide a significant source of extra income in low and middle-Income countries, given the increased demand in recent decades.

Moreover, tourism and food fads have increased the interest in wild insects (Perdue, 2018; Baker et al., 2019). The narrative of insects as the enemy comes from marketing pesticides to farmers (Lesnik, 2019). This false perception has resulted in ecocide, drastically reducing their number and biodiversity. Pesticides kill insects and harm the environment, polluteing the soil and groundwater aquifers. The consequences are devastating and include biodiversity loss, especially in the insect population (Beketov et al., 2013). The use of insecticides varies worldwide, with levels as high as 32.2 kg/ha recorded in the Bahamas compared with 0.29 kg/ha in India (Sharma et al., 2020). According to the WHO, more than 300,000 human deaths every year worldwide are directly related to pesticide use (Sharma et al., 2020). In addition, a potential risk exists for sensitive population segments, which is reflected in a higher incidence of cancer (Kim et al., 2017). The importance of insects in ecosystem restoration and maintenance has started to be considered in recent years. A recent study (Covert et al., 2020) estimated the toxicity of pesticides to aquatic life in streams in the U.S. between 2013 and 2017 and found 13 insecticides with potential toxicity in watersheds. Systemic insecticides show sublethal effects on fish, reptiles, frogs, birds, and mammals and impact ecosystem services and functioning. Insecticides have resulted in reduced soil biota, pollinator insects, and aquatic invertebrate communities (Pisa et al., 2021).

Sustainable insect harvesting

The solution to insect ecocide is complex but calls for sustainable harvesting of insects in combination with the conservation of their habitats, which includes protecting the diversity of wild plants. Many traditional cultures still consume insects as biological control during the harvesting season. The argument for the conventional use of pest insects as food has been widely discussed (Lesnik, 2018). Cerritos (2008) demonstrated the economic and environmental benefits of harvesting the *chapulín* (grasshopper species) from cornfields in Mexico as an alternative to pesticides for controlling pests. *Chapulín* (grasshopper) grows during the rainy season (from June to October) when the plants are young. Several authors have proposed the development of legally regulated management protocols for recording biological information on the different species and thus supporting their conservation (Babarinde et al., 2020; Dürr et al., 2020; Musundire et al., 2021). They have also called for implementing seasonal restrictions, with open seasons when harvesting is permitted, followed by closed seasons. Yen (2015b) has recommended that each species be assessed based on biological factors such as its distribution, habitat, host plants, life cycle characteristics, seasonality, and distribution capacity. The same study recommends evaluating the potential of domestication or semi-domestication to reduce the overharvesting of wild insects. In addition, there are external factors to consider, such as local management, traditional knowledge, demand, marketing, and the product's commercial value (Gahukar, 2020).

For insects that have more than two generations per year, an efficient measure would be not to harvest the first generation to ensure the survival of some larvae and protect against potentially damaging external factors, such as droughts and fires (Hochkirch, 2016). Some researchers have proposed an international research center for insect conservation that would help maintain their diversity, abundance, rational use, and control. Scientific research, data collection, and citizen education are the basis for knowing the importance and favor of preserving terrestrial invertebrates (nematoda, annelida, mollusca, and arthropoda) (Harvey et al., 2020a). Governments, science funders and environmental agencies need to invest in centers for invertebrate conservation and assess their conservation status. A primary objective with people consists of encouraging and guiding action, building capacity, and raising awareness of invertebrates' global and national importance (Hochkirch, 2016), changing the perception that insects are just pests.

Many potentially edible insect species and their ability to breed rapidly provide the potential to promote entomophagy for insect conservation when sustainable harvesting protocols are established (van Huis and Oonincx, 2017). Especially in poor rural areas, insects would be an interesting economical protein source. So, when entomophagy is linked to sustainable harvesting, it is hypothesized that they may contribute to the conservation of biodiversity because:

(1) it may reduce chemical pesticides and promote sustainable wild harvesting as biological control of the insects.

(2) it can stimulate the protection and conservation of insects as traditional food sources, thus leading to their economic and cultural re-evaluation.

(3) it can improve the content of organic matter, the capture of carbon dioxide, and the soil's oxygenation.

(4) it may promote the use of biological pesticides that can target specific pests of primary concern without affecting the broader environment.

(5) the income from the annual harvest of wild insects may be an incentive to conserve wild insects.

Nutritional aspects

There is a current interest in replacing conventional animal protein sources with more sustainable alternatives of similar nutritional quality because of their negative impact on the environment (Imathiu, 2020). The meat crude protein content varies from 23 g/100 g in chicken to 35 g/100 g in pork on a dry matter basis (Menezes et al., 2018), while the crude protein content of most farmed edible insects ranges from 20 to 76% on a dry matter basis. However, the composition of edible insects varies from the species, feed, environmental aspects, and the development stage of the insect. Then, the fat content can vary from 2 to 50% in dry matter, an excellent source of polyunsaturated fatty acids (even more than 70% of the total fatty acids). In addition, insects have carbohydrates, mainly chitin, as part of their exoskeleton. Finally, many proteins (B, A, D, E and K) and minerals (K, Na, Ca, Cu, Fe, Zn, mg, and P) have been found in different species (Kourimská and Adámková, 2016). However, the amount of true protein that insects possess be overestimated due to the presence of chitin when the protein is determined by the Kjeldahl method (Jonas-Levi and Martinez, 2017). There are many reviews on this topic focused on different species, gender differences and other aspects (Kulma et al., 2020; Meyer-Rochow et al., 2021; Ojha et al., 2021; Orkusz, 2021).

The wide variety of genetically diverse species consumed in different life stages (eggs, pupa, or adult), as well as larvae (Lepidoptera and Coleoptera), explains why insects may have very different nutritional compositions at different stages. However, the nutritional value of wild edible insects is not well known because of their high diversity in species and stages of consumption.

Increasing the consumption of insects as a high-quality source of protein has been put forward as an essential avenue for achieving SDGs (sustainable development goals) from a nutritional and environmental point of view (Dicke, 2018; Crespo-Pérez et al., 2020). In addition, an Indian reach concluded that insect collection should be environmentally sustainable (Chakravorty et al., 2016).

The bioavailability of macronutrients and micronutrients is not explored enough, and contradictory findings reports have been reported with different insect species and processing conditions. Moreover, the presence of antinutritional compounds has been poorly considered (Ojha et al., 2021).

Insects are a rich source of potential nutraceutical compounds (Ramos-Elorduy, 1997; Hurd et al., 2019; Abril et al., 2022). Then, some insects are an interesting source of polyphenols (such as carotenoids and flavonoids). Moreover, the hydrolysates of the high-quality protein fraction both for enzymatic and fermentation technics may exert biological activities such as antioxidant, antimicrobial and antihypertensive, helping to prevent many common human diseases like hypertension and diabetes (Mendoza-Salazar et al., 2021; Villaseñor et al., 2021).

Insects can help with metabolic syndrome complications, especially oxidative stress, inflammation, and metabolic disorders, although the most studied insects are farmed insects such as *Tenebrio molitor* Linnaeus, 1,758 (Coleoptera, Tenebrionidae) and *Hermetia illucens* Linnaeus, 1,758 (Diptera, Stratiomyidae) (Navarro del Hierro et al., 2022). In this sense, few types of research have been done on cellular and animal models, but most of them displayed radical scavenging or metal ion chelation properties and modulation of antioxidant enzymes. Moreover, animal models have shown a decrease in the content of markers of oxidative damage markers induced by dietary stress (D'Antonio et al., 2021).

Finally, diverse authors have widely analyzed the safety of consuming wild edible insects for the consumer's concerns and legislative requirements, especially in Europe. Many concerns are related to the allergenicity potential of wild species and the biological hazards because of the abuse of pesticides. However, most researchers have shown that the processing methods can reduce some risks because of insects' high temperatures and allergenicity, like other food products (Murefu et al., 2019; Imathiu, 2020).

Legislative considerations

The welfare of invertebrate animals has been recently discussed by (Carere and Mather, 2019), who focused on animals for experimental purposes. However, there is no legislation governing the harvesting or farming of insects. Moreover, there are no guidelines or procedures for killing insects before consumption. Finally, there are no rules on the use of pesticides based on insects' perspectives related to the concerns about the use of pest insect chemicals on the insect's welfare (Wing, 2021).

The absence of specific laws regulating trade, production, harvesting, and other aspects limits the expansion of this industry (Wilderspin and Halloran, 2018). Firstly, it should be noted that there is no easy solution for regulating this industry at the international level. Guidelines should be adapted to each country's culture, economy, and even religious traditions (Mishyna et al., 2020). This difficulty may explain the absence of international rules for the edible insect industry, although the Food and Agriculture Organization and the United Nations consider insects the "food of the future" (Holm et al., 2018).

Few countries have legislation on edible insects and are focused on commercializing insects for human and/or animal food purposes, including hygiene and safety considerations (Grabowski and Klein, 2017; Li et al., 2021). Very few pieces of legislation deal with the ethical aspects of harvesting edible insects. Unfortunately, the existing laws do not protect insects in their natural ecosystems. There are no provisions prohibiting overharvesting, no legally defined collection periods to protect biodiversity, and no measures to preserve the ecosystem for future generations. Thus, international, national, and local legislations are needed to ensure sustainable harvesting from the wild and controlled farming. These legal measures must consider the requirements of individual species and consumers' preferences. Ethical regulations face two main problems: the perception of insects as only agricultural pests and the controversial belief that insects do not feel pain. It is widely thought that insects do not feel pain because they do not have nociceptors, so they do not need legal protection against pain and harm.

Based on the criteria for considering whether a being is sentient, particularly the presence of a nervous system that can process information, it is reasonable to conclude that many invertebrate animals, including insects, are sentient. This makes practices that cause substantial harm, such as their exploitation for consumption as food, questionable for many people. Keep in mind that the death of insects is expected in the wild and tends to occur massively. Even on insect farms, early death is common. For example, 99% of crickets fed on food scraps and straw die within 3 months (Lundy and Parrella, 2015).

There is little knowledge about how invertebrate animals experience pain and what stimuli are painful. In addition, getting these animals to lose consciousness is not easy. Therefore, it is not possible to ensure that the various methods of killing them are painless. The rejection in many countries regarding the consumption of insects focuses on the fact that they do not have legislation on breeding these animals for this purpose besides the neophobia and disgust about their consumption. However, consumption has increased over the past few years due to the promotion and advocacy of insect consumption by the Food and Agriculture Organization of the United Nations and other institutions (FAO., 2021).

Another ethical aspect regarding using insects for food raises specific safety issues, including whether insect consumption could harm human health. Although the longstanding tradition of eating insects in tropical countries (Ingram, 2019; Murefu et al., 2019), many food safety concerns have been raised, especially in Europe. Research currently focuses on the potential presence of pathogenic microorganisms, allergenic substances, parasites, toxic compounds, and pesticide residues (Fels-Klerx et al., 2018), not on concerns related to wild harvesting.

In this regard, the EFSA (European Food Safety Authority) has published a report (Committee, 2015) that compares the risks associated with consuming insects and other foods of animal origin. The report recognizes the lack of information on the risks associated with eating insects, especially wild-harvested ones, given the limited amount of available safety data. The highest microbiological risks are cross-contamination, poor hygiene, and inappropriate handling during processing and storage. Pesticides and pesticide residues have not been studied a lot, although harvested insects may pose a risk given the excessive use of these substances in industrial agriculture (Committee, 2015). Poma et al. (2017) investigated the levels of organic contaminants and metals in composite samples of the greater wax moth, migratory locust, mealworm beetle, and buffalo worm. Four insect-derived food products marketed in Belgium were also characterized. Insects and food products from insects authorized for human consumption were purchased from various shops, e-shops, and supermarkets in Belgium. They were found to contain low levels of organic contaminants and metals. These levels are generally lower than those commonly consumed in animal products (de Paepe et al., 2019).

Despite being consumed since prehispanic times, Mexico does not have specific insect legislation (Ramos Elorduy et al., 2006). Instead, at the safety level, insects are considered between "other meat products" in the local normativity (DOF-Diario Oficial de la Federación, 2022). Moreover, there is no legislation about the sustainable requirements of wild insects or their sacrifice under ethical conditions (Carreño, 2022).

So, as a first step, it is essential to create international and national legislation focused on insects as a food source, considering insects' welfare and food safety for human consumption and establishing guidelines and standards that guarantee sustainable harvesting. A second step would be disseminating clear, accurate scientific and well-documented information about the benefits of eating insects for the health and the environment. The adverse reaction to insects among the public can be attributed to the fact that in the Western world, during much of the history of agricultural and livestock production, insects have been viewed as pests that should be eradicated (Schmidt, 2008). However, in the Western world, the development of new insect-based products is increasing in the market (Melgar-Lalanne et al., 2019). On the other hand, tropical countries like Mexico, Thailand and Nigeria have different perspectives. Here, wild insects harvested from agricultural lands and forests are a rich resource of food and income (Vega Mejía et al., 2018; Lesnik, 2019).

Furthermore, there is enough evidence that the primary factor behind the negative attitude toward consuming insects is food neophobia (fear of eating new or unknown foods) (Verbeke, 2015). Therefore, it is interesting to consider that if perceptions of insects improved, people would be more appreciative, curious about, and empathetic toward these invertebrates (Looy et al., 2014). However, this strategy could have the opposite effect, given that when animals are included in the human diet, people tend to view them solely as a source of nutrients (Gjerris et al., 2016). That is why the management of information about the consumption of insects as food must be careful and cover all aspects that involve it, from ecological, ethical, nutritional, functional, and even sociocultural.

Pest insects as food: A mexican perspective

With more than 500 species of edible insects, Mexico is one of the three principal countries where entomophagy is practiced (Jongema, 2020). So, aphids, beetles, butterflies, flies, grasshoppers, maguey worms, ants and bedbugs are the most found in different regions.

Most of the edible species are only consumed locally by rural and indigenous populations. They are collected from nearby forests and agricultural fields during the rainy season and cannot be found in the regional and national markets. However, the consumption of some of the wild edible Mexican species is trendy, and it is possible to find them in gourmet stores, prehispanic restaurants and even online stores. *Chapulín* (grasshopper, Pyrgomorphidae), chicatana (ant queen, *Atta mexicana* Smith, 1,858, Hymenoptera, Formicidae), *chinicuil* or red maguey worm (*Comadia redtenbacheri* Hammerschmidt, 1,848, Lepidoptera, Cossidae) and white maguey worm (*Aegiale hesperiaris* Walker 1,856, Lepidoptera, Hesperiidae) are probably the most studied at the scientific level.

Chapulín (grasshoppers, *Pyrgomorphidae*) is the best-known Mexican insect worldwide. More than 20 species of edible *chapulín* have been identified. All of them belong to the *Pyrgomoprhidae* family, like the genus *Sphenarium,* many from the family *Acridae,* and some from the family *Romaleidae* (Jongema, 2015). The chapulín (grasshopper) grows mainly in cornfields ("*milpa*"), as well as in alfalfa, soya, barley, and peanut fields. They are collected during the rainy season, from June to October, when the plants are still young. However, this traditional and novelty gourmet insect (Youssef and Spence, 2021), consumed in its whole form and incorporated into bar snacks, is also a dangerous agricultural pest. This insect is responsible for significant economic losses for several staple foods such as corn, bean, alfalfa, squash, and broad bean, mainly green leaves. The usual control method consists in applying organophosphorus insecticides. This practice is dangerous for farmers and the environment, especially subsistence agricultural workers. On the other side, the traditional and more sustainable control method is their collection during the rainy season (May to December). A farmer could capture between 50 and 70 kg /week of grasshoppers. At this level, the harvesting of grasshoppers could be considered a sustainable pest control method in the region (Cerritos and Cano-Santana, 2008). Unfortunately, the increase in domestic demand has promoted overharvesting. So, in the municipality of Tepatepec (Hidalgo, Mexico) (Pino-Moreno et al., 2020), a reduction in the collection of insects has recently been reported, with the local population attributing it to climate change, irrational exploitation, and

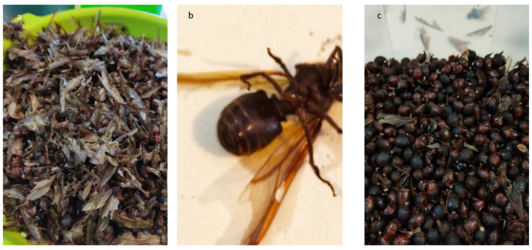

FIGURE 1
(a) Wildly collected *chicatana* (*Atta mexicana*), **(b)** A specimen of *Atta mexicana*, **(c)** *Chicatana* prepared for cooking from Jalcomulco-Huatusco region (Veracruz, Mexico). *Source: Authors own pictures.*

FIGURE 2
Traditional *Chicatana* (*Atta mexicana*) chili sauce. *Source: Authors own picture.*

scarcity due to the progress of urban development, pollution, the introduction of livestock, and a lack of traditional knowledge which increases hunting and capture, commercial plundering, irrational consumption, and excessive sales and misuse of the source, combined with a rise in selling prices. A similar phenomenon has been observed for the *chicatana* ant in the coffee plantations of Huatusco (Figure 1) (Veracruz, Mexico) (Escamilla-Prado et al., 2012).

Atta mexicana Smith, 1,858 (Hymenoptera, Formicidae) *(chicatana*) is the queen ant of a leaf-cutting ant distributed in the Neotropical area and considered a pest in agricultural and silviculture, responsible for significant losses in citrus, cacao, and corn, ornamental plants, and amaranth cultivations, among others. They cultivate the symbiotic fungus *Leucoagaricus gongylophorus (Möller)* (Infante-Rodríguez et al., 2020) and cut trees' leaves to feed the fungus. The fertilized females establish new colonies solitarily after the nuptial flight when queen ants have been reported to be highly aggressive among them, attaching and killing each other (Sánchez-Peña, 2008). The *chicatana* (queen ant) is collected during the nuptial flight. The nuptial flight occurs in Mexico in May and June, usually at dawn. Before leaving the nest of origin, males and females fly to reproduce and establish new anthills. After the nuptial flight, the queens land on the ground, shed their wings, and excavate the soil. After 6 to 10 h of digging, a tunnel and a chamber are obtained (Phillips et al., 2021). Peasants and indigenous people harvest the queen ants just after the nuptial light avoiding that the ants can establish new anteaters in surrounding crop areas. The queen ants (*chicatanas*) have a local gastronomic value and could be sold for as much as 40 USD when cleaned (wings, head and thorax removed), as shown in Figure 1c (2022, local prices reported in Huatusco, Veracruz, Mexico) and as whole ∼5–10 USD (Figure 1a). The cleaning process is laborious and eliminates the ant's wings and the top section (head and thorax) from the queen ant. Afterward, the abdomen is roasted or fried and cooked in chili sauce, made with tomato and hot pepper (Figure 2). *Chicatana* (queen ant) is a traditional remedy for arthritis and rheumatism. Despite their cultural and economic importance, they are still regarded as a pest that must be eliminated, putting them at risk of extinction. During the last decade, the insect harvesting season has decreased because of the number of individuals due to insecticides, mostly fipronil, a highly toxic one (Mota Filho et al., 2021), similarly to those reported in Mexico by different authors (Cerritos Flores et al., 2014; Cerritos and Klewer, 2015).

A similar situation has been observed for *Comadia redtenbacheri* Hammerschmidt 1,848 (Lepidoptera: Cossidae) (red agave worm or *chinicuil*) (Figure 3) and in *Aegiale hesperiaris* Walker 1,856 (Lepidoptera: Hesperiidae) (white maguey worm or *meocuil*), which are consumed at the larvae stage. Both insects are pests in *Agave salminana* (maguey) because they grow in the leaves and roots and drill the plant. The red worm is considered a gourmet food item with nutritional benefits. To date, it has not been feasible to rear these maguey worms under greenhouse conditions, and sustained wild harvesting is putting them in danger of extinction (Molina-Vega et al., 2021). The harvesting of white and red worms from maguey is a vital income source for communities from the states of Hidalgo and Tlaxcala in Mexico. However, this activity is intensive, and stationery and collectors do not have the proper training for worm extraction. Then it is essential to apply organizational, training, and selling strategies for their sustainable use to reduce the environmental impact of this practice (de Luna-Valadez et al., 2013). Fortunately, some environmental techniques based on semi-wild harvesting have been explored in the last years, like the artificial infestation to increase the worm population in the *Agave salmiana* (Espinosa-García et al., 2018). The consequences of the extinction of Mexican wild edible insects were studied inside the *me'phaa* community in Guerrero (Mexico). A traditional food source is at risk due to biodiversity loss in the edible terrestrial

FIGURE 3
Red agave worm taco *(Comadia redtenbacheri)* in Calpulalpan, Tlaxcala, Mexico. *Source: Authors own picture.*

fauna over the last 40 years. Overharvesting is one of the factors which put on at risk of extinction some insects like grasshoppers, crickets, and butterflies (García Hilario et al., 2016).

The loss of indigenous knowledge about the selective harvesting of insects should be rescued. It would be the base for educational initiatives (Hlongwane et al., 2021; Musundire et al., 2021). These local-scale initiatives can act as models for scaling up projects and programmes for the sustainable utilization of edible insects in the wild. Although policies that encompass other issues, such as preserving trees, forests, and water resources, exist, stewardship aspects of the utilization of edible insects are grossly overlooked. Therefore, there is an urgent need for special consideration for national support for building and supporting the insect sector (Musundire et al., 2021). In Mexico, some efforts have been made in formal and non-formal environmental education, mostly in children from rural areas (López-Gómez and Bastida Izaguirre, 2018; Pineda Jiménez et al., 2018). However, few of these programs have been centered on insects, and, to our knowledge, no efforts in the sustainable harvesting of edible insects have been implemented in the region.

Conclusion and future trends

Insects are vital for ecosystem regulation. Their biodiversity and abundance are essential in many ecological processes like soil regeneration and pollination. Traditionally, they are a common source of food and medicine for many communities in tropical areas. At the time, human consumption might help biological pest control. However, the development of industrial agriculture, even between subsistence agriculture, and the increase in the demand for some local insects have put some of them at risk of extinction. Native people are aware of the local insects present in their communities. They know their life cycles and habitats, the appropriate season to harvest them, and how to promote their reproduction when required. Unfortunately, this knowledge is getting lost. Economic resources for entomology and entomophagy are needed. Although in countries like Mexico, insects have been well-known since prehispanic times, the use of new instruments for basic research will provide different strategies to maintain the biodiversity and abundance of wild insects. Its use as food and feed has been one of the most studied in the past decade. Wild insects are widely appreciated in many regions. Moreover, their consumption is rising in the Western World, thus, attracting the interest of consumers for sustainable and nutritional food sources such as insects.

Local collectors should be trained in sustainable techniques for harvesting insects. Thus, they need to know the characteristics of each local insect to avoid overexploitation and extinction. A sustainable alternative would be open and closed seasons for harvesting to guarantee the future populations of insects. Moreover, sustainable farmers should be taught the correct application of pesticides and biological pest control to reduce pesticide residues in edible insects. Farmers also need training about ethical aspects related to insect welfare.

Finally, environmental considerations related to harvesting edible insects as food should be addressed in local, national, and international laws and regulations to protect insects and their ecosystem. Thus, the necessity of studying insect ecology, including their life cycles, environments, and diets, should be implemented to develop protective legislation for edible insects and ecosystems. This necessity is urgent in traditional consumer countries like Mexico, where many insects are at risk of extinction.

Author contributions

GM-L: conceptualization, supervision, formal analysis, writing the original draft, writing review, editing, and supervision. IP-D: formal analysis, research, and writing the original draft. ER-M: research, writing the original draft, and editing. DH-R: research, formal analysis, writing the original draft, and editing. RZ: formal analysis, editing, and review. All authors contributed to the article and approved the submitted version.

Funding

IP-D received a scholarship for doctoral studies in Biomedical Sciences from the National Council of Science and Technology (CONACYT), scholarship holder number: 783845. DHR received a postdoctoral grant from CONACYT with project number I1200/224/2021. "Esta obra fue publicada gracias al apoyo del Consejo Veracruzano de Investigación Científica y Desarrollo Tecnológico".

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abril, S., Pinzón, M., Hernández-Carrión, M., and Sánchez-Camargo, A. del P. (2022). Edible insects in latin America: a sustainable alternative for our food security. *Front. Nutr.* 9, 967. doi: 10.3389/fnut.2022.904812

Babarinde, S. A., Mvumi, B. M., Babarinde, G. O., Manditsera, F. A., Akande, T. O., and Adepoju, A. A. (2020). Insects in food and feed systems in sub-Saharan Africa: the untapped potentials. *Int. J. Trop. Insect. Sci.* 41, 1923–51. doi: 10.1007/s42690-020-00305-6

Baker, M. A., Legendre, T. S., and Kim, Y. W. (2019). "Edible insect gastronomy," in *The Routledge Handbook of Gastronomic Tourism* (London: Routledge), 412–419. doi: 10.4324/9781315147628-50

Balla, A., Silini, A., Cherif-Silini, H., Chenari Bouket, A., Moser, W. K., Nowakowska, J. A., et al. (2021). The threat of pests and pathogens and the potential for biological control in forest ecosystems. *Forests.* 12, 1579. doi: 10.3390/f12111579

Beketov, M. A., Kefford, B. J., Schäfer, R. B., and Liess, M. (2013). Pesticides reduce regional biodiversity of stream invertebrates. *Proc. Natl. Acad. Sci. U.S.A.* 110, 11039–11043. doi: 10.1073/pnas.1305618110

Carere, C., and Mather, J. (2019). *The Welfare of Invertebrate Animals.* Springer Nature Switzerland AG. doi: 10.1007/978-3-030-13947-6

Carreño, D. (2022). *Muy nutritivos, pero los insectos comestibles en México están al margen de la ley-Goula.* Available online at: https://goula.lat/muy-nutritivos-pero-los-insectos-comestibles-en-mexico-estan-al-margen-de-la-ley/

Cerritos Flores, R., Ponce-Reyes, R., and Rojas-García, F. (2014). Exploiting a pest insect species *Sphenarium purpurascens* for human consumption: ecological, social, and economic repercussions. *J. Insects Food Feed.* 1, 75–84. doi: 10.3920/JIFF2014.0013

Cerritos, R. (2008). Grasshoppers in agrosystems: pest or food. *Anim. Sci. Rev.* 2011, 41. doi: 10.1079/PAVSNNR20116017

Cerritos, R., and Cano-Santana, Z. (2008). Harvesting grasshoppers *Sphenarium purpurascens* in Mexico for human consumption: a comparison with insecticidal control for managing pest outbreaks. *Crop Prot.* 27, 473–480. doi: 10.1016/j.cropro.2007.08.001

Cerritos, R., and Klewer, M. (2015). Prehispanic agricultural practices: using pest insects as an alternative source of protein. *Anim. Front.* 5, 31–36. doi: 10.2527/af.2015-0017

Chakravorty, J., Ghosh, S., Megu, K., Jung, C., and Meyer-Rochow, V. B. (2016). Nutritional and antinutritional 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. doi: 10.1016/j.aspen.2016.07.001

Committee, E. S. (2015). Risk profile related to production and consumption of insects as food and feed. *EFSA J.* 13, 4257. doi: 10.2903/j.efsa.2015.4257

Covert, S., Alex., Shoda, M. E., Stackpoole, S. M., and Stone, W. W. (2020). Pesticide mixtures show potential toxicity to aquatic life in U.S. streams, water years 2013–2017. *Sci. Total Environ.* 745, 141285. doi: 10.1016/j.scitotenv.2020.141285

Crespo-Pérez, V., Kazakou, E., Roubik, D. W., and Cárdenas, R. E. (2020). The importance of insects on land and in water: a tropical view. *Curr. Opin. Insect Sci.* 40, 31–38. doi: 10.1016/j.cois.2020.05.016

D'Antonio, V., Serafini, M., and Battista, N. (2021). Dietary modulation of oxidative stress from edible insects: a mini-review. *Front. Nutr.* 8, 38. doi: 10.3389/fnut.2021.642551

de Luna-Valadez, B., Macías-Rodríguez, F. J., Esparza-Frausto, G., León-Esparza, E., Tarango-Arámbula, L. A., Méndez-Gallegos, S., et al. (2013). Recolección de insectos comestibles en Pinos Zacatecas: descripción y análisis de la actividad. *Agroproductividad.* 6, 35–44. Available online at: https://link.gale.com/apps/doc/A382430306/IFME?u=anon~45828343&sid=googleScholar&xid=76bd1716

de Paepe, E., Wauters, J., van der Borght, M., Claes, J., Huysman, S., Croubels, S., et al. (2019). Ultra-high-performance liquid chromatography coupled to quadrupole orbitrap high-resolution mass spectrometry for multi-residue screening of pesticides, (veterinary) drugs and mycotoxins in edible insects. *Food Chem.* 293, 187–196. doi: 10.1016/j.foodchem.2019.04.082

Dicke, M. (2018). Insects as feed and the sustainable development goals. *J. Insects Food Feed.* 4, 147–156. doi: 10.3920/JIFF2018.0003

DOF-Diario Oficial de la Federación (2022). Available online at: https://www.dof.gob.mx/nota_detalle.php?codigo=2081721andfecha=11/07/2005#gsc.tab=0 (accessed October 10, 2022).

Dürr, J., Andriamazaoro, H., Nischalke, S., Preteseille, N., Rabenjanahary, A., Randrianarison, N., et al. (2020). "It is edible, so we eat it": Insect supply and consumption in the central highlands of Madagascar. *Int. J. Trop. Insect Sci.* 40, 167–179. doi: 10.1007/s42690-019-00067-w

Edwards, E., Toft, R., Joice, N., and Westbrooke, I. (2017). The efficacy of Vespex® wasp bait to control Vespula species (Hymenoptera: Vespidae) in New Zealand. 63, 266–272. doi: 10.1080/09670874.2017.1308581

Escamilla-Prado, E., Escamilla-Femat, S., Gómez-Utrilla, J. M., Andrade, M. T., Ramos-Elorduy, J., and Pino-Moreno, J. M. (2012). Uso tradicional de tres especies de insectos comestibles en agroecosistemas cafetaleros del estado de Veracruz. *Trop. Subtrop. Agroecosystems.* 15, S101–S109.

Espinosa-García, N., Llanderal-Cázares, C., Miranda-Perkins, K., Vargas-Hernández, M., González-Hernández, H., and Romero-Nápoles, J. (2018). Infestación Inducida de Gusano Rojo *Comadia redtenbacheri* en *Agave salmiana*. *Southwest. Entomol.* 43, 1009–1019. doi: 10.3958/059.043.0418

FAO. (2021). *Looking at Edible Insects From A Food Safety Perspective: Challengers and Opportunities for the Sector.* Rome. doi: 10.4060/cb4094en

Fels-Klerx, H. J., van der, Camenzuli, L., Belluco, S., Meijer, N., and Ricci, A. (2018). Food safety issues related to the uses of insects for feeds and foods. *Compr. Rev. Food Sci. Food Saf.* 17, 1172–1183. doi: 10.1111/1541-4337.12385

Gahukar, R. T. (2020). Edible insects collected from forests for family livelihood and wellness of rural communities: a review. *Glob. Food Sec.* 25, 100348. doi: 10.1016/j.gfs.2020.100348

García Hilario, F., Cruz Morales, J., Castro Ramírez, A. E., Trench Hamilton, R., T., and Pacheco Flores, C. (2016). Crisis del sistema milpero: la erosión biológica y cultural en San Juan de las Nieves, Malinaltepec, Guerrero, México. *Revista de Geografía Agrícola.* 113–123. doi: 10.5154/r.rga.2016.57.003

Gjerris, M. (2015). Willed blindness: a discussion of our moral shortcomings in relation to animals. *J. Agric. Environ. Ethics.* 28, 517–532. doi: 10.1007/s10806-014-9499-6

Gjerris, M., Gamborg, C., and Röcklinsberg, H. (2016). Ethical aspects of insect production for food and feed. *J. Insects Food Feed.* 2, 101–110. doi: 10.3920/JIFF2015.0097

Grabowski, N. Th., and Klein, G. (2017). Microbiology of processed edible insect products–results of a preliminary survey. *Int. J. Food Microbiol.* 243, 103–107. doi: 10.1016/j.ijfoodmicro.2016.11.005

Harvey, J. A., Heinen, R., Armbrecht, I., Basset, Y., Baxter-Gilbert, J. H., Bezemer, T. M., et al. (2020a). International scientists formulate a roadmap for insect conservation and recovery. *Nat. Ecol. Evol.* 4, 174–176.

Harvey, J. A., Heinen, R., Gols, R., and Thakur, M. P. (2020b). Climate change-mediated temperature extremes and insects: from outbreaks to breakdowns. *Glob. Chang. Biol.* 26, 6685–6701. doi: 10.1111/gcb.15377

Hawkins, N. J., Bass, C., Dixon, A., and Neve, P. (2019). The evolutionary origins of pesticide resistance. *Biol. Rev.* 94, 135–155. doi: 10.1111/brv.12440

Hernández-Álvarez, A.-J., Mondor, M., Piña-Domínguez, I.-A., Sánchez-Velázquez, O.-A., and Melgar Lalanne, G. (2021). Drying technologies for edible insects and their derived ingredients. *Dry. Technol.* 39, 1991–2009. doi: 10.1080/07373937.2021.1915796

Hlongwane, Z. T., Slotow, R., and Munyai, T. C. (2021). Indigenous knowledge about consumption of edible insects in South Africa. *Insects.* 12, 22. doi: 10.3390/insects12010022

Hochkirch, A. (2016). The insect crisis we can't ignore. *Nature.* 539, 141. doi: 10.1038/539141a

Holm, S., Javoi,š, J., Õunap, E., Davis, R. B., Kaasik, A., Molleman, F., et al. (2018). Reproductive behaviour indicates specificity in resource use: phylogenetic examples from temperate and tropical insects. *Oikos.* 127, 1113–1124. doi: 10.1111/oik.04959

Hough, R. L. (2021). A world view of pesticides. *Nat. Geosci.* 14, 183–184. doi: 10.1038/s41561-021-00723-2

Hurd, K. J., Shertukde, S., Toia, T., Trujillo, A., Pérez, R. L., Larom, D. L., et al. (2019). The cultural importance of edible insects in Oaxaca, Mexico. *Ann. Entomol. Soc. Am.* 112, 552–559. doi: 10.1093/aesa/saz018

Imathiu, S. (2020). Benefits and food safety concerns associated with consumption of edible insects. *NFS J.* 18, 1–11. doi: 10.1016/j.nfs.2019.11.002

Infante-Rodríguez, D. A., Monribot-Villanueva, J. L., Mehltreter, K., Carrión, G. L., Lachaud, J.-P., Velázquez-Narváez, A. C., et al. (2020). Phytochemical characteristics of leaves determine foraging rate of the leaf-cutting ant *Atta mexicana* (Smith) (Hymenoptera: Formicidae). *Chemoecology.* 30, 147–159. doi: 10.1007/s00049-020-00306-4

Ingram, D. J. (2019). Julie J. Lesnik: edible insects and human evolution. *Hum. Ecol.* 47, 637–638. doi: 10.1007/s10745-019-00089-5

Jonas-Levi, A., and Martinez, J.-J. I. (2017). The high level of protein content reported in insects for food and feed is overestimated. *J. Food Compos. Anal.* 62, 184–188. doi: 10.1016/j.jfca.2017.06.004

Jongema, Y. (2015). *List of Edible Insects of the World*. Wageningen: Wageningen UR.

Jongema, Y. (2020). *List of Edible Insect Species of the World*. The Netherlands: Laboratory of Entomology, Wageningen University.

Kim, S.-K., Weaver, C. M., and Choi, M.-K. (2017). Proximate composition and mineral content of five edible insects consumed in Korea. *CYTA - J. Food.* 15, 143–146. doi: 10.1080/19476337.2016.1223172

Kourimská, L., and Adámková, A. (2016). Nutritional and sensory quality of edible insects. *NFS J.* 4, 22–26. doi: 10.1016/j.nfs.2016.07.001

Kulma, M., Kourimská, L., Homolková, D., BoŽik, M., Plachý, V., and Vrabec, V. (2020). Effect of developmental stage on the nutritional value of edible insects. A case study with Blaberus craniifer and Zophobas morio. *J. Food Compos. Anal.* 92, 103570. doi: 10.1016/j.jfca.2020.103570

Lesnik, J. J. (2017). Not just a fallback food: global patterns of insect consumption related to geography, not agriculture. *Am J Hum Biol.* 29, e22976. doi: 10.1002/ajhb.22976

Lesnik, J. J. (2018). *Edible Insects and Human Evolution*. Miami: University Press of Florida.

Lesnik, J. J. (2019). The colonial/imperial history of insect food avoidance in the United States. *Ann. Entomol. Soc. Am.* 112, 560–565. doi: 10.1093/aesa/saz023

Li, X., Wang, Y., Luo, Y., Wen, J., Li, H., Gottschalk, E., et al. (2021). Opportunities to improve China's biodiversity protection laws. *Nat. Ecol. Evol.* 5, 726–732. doi: 10.1038/s41559-021-01422-2

Looy, H., Dunkel, F., v, and Wood, J. R. (2014). How then shall we eat? Insect-eating attitudes and sustainable foodways. *Agric. Human Values.* 31, 131–141. doi: 10.1007/s10460-013-9450-x

López-Gómez, R. R., and Bastida Izaguirre, D. (2018). La importancia de la educación ambiental no formal en el medio rural: el caso de Palo Alto, Jalisco. Diálogos sobre educación. *Temas actuales en investigación educativa.* 9. doi: 10.32870/dse.v0i16.408

Lundy, M. E., and Parrella, M. P. (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. doi: 10.1371/journal.pone.0118785

Melgar-Lalanne, G., Hernández-Álvarez, A.-J., and Salinas-Castro, A. (2019). Edible insects processing: traditional and innovative technologies. *Compr. Rev. Food Sci. Food Saf.* 18, 1166–9. doi: 10.1111/1541-4337.12463

Mendoza-Salazar, A., Santiago-López, L., Torres-Llanez, M. J., Hernández-Mendoza, A., Vallejo-Cordoba, B., Liceaga, A. M., et al. (2021). *In vitro* antioxidant and antihypertensive activity of edible insects flours (Mealworm and Grasshopper) fermented with *Lactococcus lactis* strains. *Fermentation.* 7, 153. doi: 10.3390/fermentation7030153

Menezes, E. A., Oliveira, A. F., França, C. J., Souza, G. B., and Nogueira, A. R. A. (2018). Bioaccessibility of Ca, Cu, Fe, Mg, Zn, and crude protein in beef, pork and chicken after thermal processing. *Food Chem.* 240, 75–83. doi: 10.1016/j.foodchem.2017.07.090

Meyer-Rochow, V. B., Gahukar, R. T., Ghosh, S., and Jung, C. (2021). Chemical composition, nutrient quality and acceptability of edible insects are affected by species, developmental stage, gender, diet, and processing method. *Foods.* 10, 1036. doi: 10.3390/foods10051036

Mishyna, M., Chen, J., and Benjamin, O. (2020). Sensory attributes of edible insects and insect-based foods – Future outlooks for enhancing consumer appeal. *Trends Food Sci. Technol.* 95, 141–148. doi: 10.1016/j.tifs.2019.11.016

Molina-Vega, A., Hernández-Domínguez, E. M., Villa-García, M., and Álvarez-Cervantes, J. (2021). *Comadia redtenbacheri* (Lepidoptera: Cossidae) and *Aegiale hesperiaris* (Lepidoptera: Hesperiidae), two important edible insects of *Agave salmiana* (Asparagales: Asparagaceae): a review. *Int. J. Trop. Insect. Sci.* 41, 1903–1911. doi: 10.1007/s42690-020-00396-1

Mota Filho, T. M. M., Camargo, R. S., Zanuncio, J. C., Stefanelli, L. E. P., de Matos, C. A. O., and Forti, L. C. (2021). Contamination routes and mortality of the leaf-cutting ant *Atta sexdens* (Hymenoptera: Formicidae) by the insecticides fipronil and sulfluramid through social interactions. *Pest Manag. Sci.* 77, 4411–4417. doi: 10.1002/ps.6475

Murefu, T. R., Macheka, L., Musundire, R., and Manditsera, F. A. (2019). Safety of wild harvested and reared edible insects: a review. *Food Control.* 101, 209–224. doi: 10.1016/j.foodcont.2019.03.003

Musundire, R., Ngonyama, D., Chemura, A., Ngadze, R. T., Jackson, J., Matanda, M. J., et al. (2021). Stewardship of wild and farmed edible insects as food and feed in Sub-Saharan Africa: a perspective. *Front. Vet. Sci.* 8, 102. doi: 10.3389/fvets.2021.601386

Navarro del Hierro, J., Hernández-Ledesma, B., and Martin, D. (2022). "Potential of edible insects as a new source of bioactive compounds against metabolic syndrome." in *Current Advances for Development of Functional Foods Modulating Inflammation and Oxidative Stress.* (London: Academic press) 331—364. doi: 10.1016/B978-0-12-823482-2.00015-7

Ngute, A. S. K., Dongmo, M. A. K., Effa, J. A. M., Ambombo Onguene, E. M., Fomekong Lontchi, J., and Cuni-Sanchez, A. (2020). Edible caterpillars in central Cameroon: host plants, value, harvesting, and availability. *For. Trees Livelihoods.* 29, 16–33. doi: 10.1080/14728028.2019.1678526

Noble, C., Min, J., Olejarz, J., Buchthal, J., Chavez, A., Smidler, A. L., et al. (2019). Daisy-chain gene drives for the alteration of local populations. *Proc. Natl. Acad. Sci. U.S.A.* 116, 8275–8282. doi: 10.1073/pnas.1716358116

Ojha, S., Bekhit, A. E. D., Grune, T., and Schlüter, O. K. (2021). Bioavailability of nutrients from edible insects. *Curr. Opin. Food Sci.* 41, 240–248. doi: 10.1016/j.cofs.2021.08.003

O'Neill, S. L., Ryan, P. A., Turley, A. P., Wilson, G., Retzki, K., Iturbe-Ormaetxe, I., et al. (2019). Scaled deployment of *Wolbachia* to protect the community from dengue and other; *Aedes* transmitted arboviruses. *Gates Open Res.* 2, 36. doi: 10.12688/gatesopenres.12844.3

Orkusz, A. (2021). Edible insects versus meat—nutritional comparison: knowledge of their composition is the key to good health. *Nutrients.* 13, 1207. doi: 10.3390/nu13041207

Pali-Schöll, I., Binder, R., Moens, Y., Polesny, F., and Monsó, S. (2019). Edible insects–defining knowledge gaps in biological and ethical considerations of entomophagy. *Crit. Rev. Food Sci. Nutr.* 59, 2760–2771. doi: 10.1080/10408398.2018.1468731

Perdue, R. T. (2018). "Eating insects and tourism: ethical challenges in a changing world," in *Tourism Experiences and Animal Consumption* (London: Routledge), 73—86. doi: 10.4324/9781315265186-6

Phillips, Z. I., Reding, L., and Farrior, C. E. (2021). The early life of a leaf-cutter ant colony constrains symbiont vertical transmission and favors horizontal transmission. *Ecol. Evol.* 11, 11718–11729. doi: 10.1002/ece3.7900

Pineda Jiménez, C., López Medellín, X., Wehncke, E. V., and Maldonado Almanza, B. (2018). Construir sociedades comprometidas con el entorno natural: educación ambiental en niños del sur de Morelos, México. *Región y sociedad.* 30:1–25. doi: 10.22198/rys.2018.72.a896

Pino-Moreno, J. M., Rodríguez-Ortega, A., and García-Flores, A. (2020). Los insectos comestibles de tepatepec, hidalgo, México: situación actual problema y perspectivas. *Entomol. Mex.* 7, 457–463.

Pisa, L., Goulson, D., Yang, E.-C., Gibbons, D., Sánchez-Bayo, F., Mitchell, E., et al. (2021). An update of the worldwide integrated assessment (WIA) on systemic insecticides. Part 2: impacts on organisms and ecosystems. *Environ. Sci. Pollut. Res.* 28, 11749–11797. doi: 10.1007/s11356-017-0341-3

Poma, G., Cuykx, M., Amato, E., Calaprice, C., Focant, J. F., and Covaci, A. (2017). Evaluation of hazardous chemicals in edible insects and insect-based food intended for human consumption. *Food Chem. Toxicol.* 100, 70–79. doi: 10.1016/j.fct.2016.12.006

Ramos Elorduy, J., Pino, J. M., and Conconi, M. (2006). Ausencia de una reglamentación y normalización de la explotación y comercialización de insectos comestibles en México. *Folia Entomol. Mex.* 45, 291–318.

Ramos-Elorduy, B. J. (1997). The importance of edible insects in the nutrition and economy of people of the rural areas of Mexico. *Ecol. Food Nutr.* 36, 347–366. doi: 10.1080/03670244.1997.9991524

Ramos-Elorduy, J. (2006). Threatened edible insects in Hidalgo, Mexico and some measures to preserve them. *J. Ethnobiol. Ethnomed.* 2, 51. doi: 10.1186/1746-4269-2-51

Sánchez-Bayo, F., and Wyckhuys, K. A. G. (2019). Worldwide decline of the entomofauna: a review of its drivers. *Biol. Conserv.* 232, 8–27. doi: 10.1016/j.biocon.2019.01.020

Sánchez-Peña, S. R. (2008). Observations on agression in leaf-cutting ant females, *Atta mexicana* (Hymenoptera: Formicidae) in Mexico. *Entomol. News.* 119, 541–544. doi: 10.3157/0013-872X-119.5.541

Schmidt, C. W. (2008). The yuck factor: when disgust meets discovery. *Environ. Health Perspect.* 116, A524–A527. doi: 10.1289/ehp.116-a524

Sharma, A., Shukla, A., Attri, K., Kumar, M., Kumar, P., Suttee, A., et al. (2020). Global trends in pesticides: a looming threat and viable alternatives. *Ecotoxicol. Environ. Saf.* 201, 110812. doi: 10.1016/j.ecoenv.2020.110812

Siviter, H., Brown, M. J. F., and Leadbeater, E. (2018). Sulfoxaflor exposure reduces bumblebee reproductive success. *Nature.* 561, 109–112. doi: 10.1038/s41586-018-0430-6

Tomasetto, F., Tylianakis, J. M., Reale, M., Wratten, S., and Goldson, S. L. (2017). Intensified agriculture favors evolved resistance to biological control. *Proc. Natl. Acad. Sci. U S A.* 114, 3885–3890. doi: 10.1073/pnas.1618416114

van Huis, A., and Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed. A review. *Agron. Sustain. Dev.* 37, 43. doi: 10.1007/s13593-017-0452-8

van Itterbeeck, J., and Pelozuelo, L. (2022). How many edible insect species are there? a not so simple question. *Diversity.* 14, 143. doi: 10.3390/d14020143

Vega Mejía, N., Ponce Reyes, R., Martinez, Y., Carrasco, O., and Cerritos, R. (2018). Implications of the western diet for agricultural production, health and climate change. *Front. Sustain. Food Syst.* 2, 88. doi: 10.3389/fsufs.2018.00088

Verbeke, W. (2015). Profiling consumers who are ready to adopt insects as a meat substitute in a Western society. *Food Qual. Prefer.* 39, 147–155. doi: 10.1016/j.foodqual.2014.07.008

Villaseñor, V. M., Enriquez-Vara, J. N., Urías-Silva, J. E., and Mojica, L. (2021). Edible Insects: techno-functional properties food and feed applications and biological potential. *Food Rev. Int*. 1–27. doi: 10.1080/87559129.2021.1890116. [Epubh ahead of print].

Wilderspin, D. E., and Halloran, A. (2018). "The effects of regulation, legislation and policy on consumption of edible insects in the global south," in *Edible Insects in Sustainable Food Systems* (Springer Nature Switzerland AG), 443–455. doi: 10.1007/978-3-319-74011-9_28

Wing, K. D. (2021). Pharmaceutical technologies with potential application to insecticide discovery. *Pest Manag. Sci.* 77, 3617–3625. doi: 10.1002/ps.6075

Wolff, J. N., Gemmell, N. J., Tompkins, D. M., and Dowling, D. K. (2017). Introduction of a male-harming mitochondrial haplotype via 'trojan females' achieves population suppression in fruit flies. *Elife.* 6:e23551. doi: 10.7554/eLife.23551

Yen, A. L. (2015a). Conservation of Lepidoptera used as human food and medicine. *Curr. Opin. Insect Sci.* 12, 102–108. doi: 10.1016/j.cois.2015.11.003

Yen, A. L. (2015b). Insects as food and feed in the Asia Pacific region: current perspectives and future directions. *J. Insects Food Feed.* 1, 33–55. doi: 10.3920/JIFF2014.0017

Youssef, J., and Spence, C. (2021). Introducing diners to the range of experiences in creative Mexican cuisine, including the consumption of insects. *Int. J. Gastron. Food Sci.* 25, 100371. doi: 10.1016/j.ijgfs.2021.100371