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REVIEW
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Review: Insects—A Source of Safe and Sustainable Food?— "Jein" (Yes and No)

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For almost a decade, edible insects have become promoted on a wider basis as one way to combat world hunger and malnourishment, although attempts to do so have a longer history. Contemporary researchers and consumers, particularly those without an entomophagous background, have been rising safety and sustainability concerns. The present contribution seeks a substantiated answer to the question posed above. The possible answer consists of different factors that have been taken into consideration. First, the species and its life cycle. It is mandatory to realize that what is labeled as "edible insects" stands for more than 2,140 animal species, not counting other edible, non-crustacean arthropods. Their life cycles are as diverse as the ecological niches these animals can fill and last between some days to several years and many of them may—or may not—be reproduced in the different farming systems. Second, the level of knowledge concerning the food use of a given species is important, be it traditional, newly created by research, or a combination of both. Third, the existence of a traditional method of making the use of the insect safe and sustainable, ideally from both the traditional and the modern points of view. Fourth, the degree of effectiveness of these measures despite globalization changes in the food-supplying network. Fifth, farming conditions, particularly housing, feeding (type, composition, and contaminants), animal health and animal welfare. Sixth, processing, transport, and storage conditions of both traditional and novel insect-based foodstuffs, and seventh, consumer awareness and acceptance of these products. These main variables create a complex web of possibilities, just as with other foodstuffs that are either harvested from the wild or farmed. In this way, food safety may be reached when proper hygiene protocols are observed (which usually include heating steps) and the animals do not contain chemical residues or environment contaminants. A varying degree of sustainability can be achieved if the aforementioned variables are heeded. Hence, the question if insects can be safe and sustainable can be answered with "jein," a German portmanteau word joining "yes" ("ja") and "no" ("nein").

Keywords: entomophagy, ancestral, tradition, food safety, insect gathering, insect farming, productive insects, xiroculture

INTRODUCTION

Sustainability was declared one of the goals for the world population, based on a UN decision,[1] and many political entities have expressed their commitment, e.g., EC.[2] Caution is one of the principles of food policies worldwide, making e.g., food safety one of the pillars of European Community (EC, vel EU for European Union) food legislation (Barlow et al., 2015).

Although practiced by our hominine ancestors from prehistoric times on (Payne et al., 2019), it has been from the 2010s on that consuming edible insects (entomophagy) has started to gain more attention beyond its traditional boundaries. Questions regarding their food safety and sustainability have been raised (e.g., Van Huis et al., 2013; Smetana et al., 2016; Dicke, 2018; Berggren et al., 2019; Chia et al., 2019; Guiné et al., 2021), and reclaiming both sustainability and food safety for "the" insects has been observed frequently and was taken up by the media.[3] In consequence, the overall opinion of the general public, particularly in Western countries, is that insects are both safe and sustainable. However, comments on the matter have been given from biological and non-biological points of view and have been ranging from denial to approval, showing the complexity of the issue. In fact, both extremes can be correct, due to a series of influencing factors. This is why the German term "jein" was used. It is an accepted fusion of "ja" (yes) and "nein" (no) and is typically used when a polar (yes/no) question is too complex to answer truthfully with either "yes" or "no" (Bücker, 2013). It has also been used in scientific literature (e.g., Barth et al., 2005).

In this way, the goal of this review is to provide some key parameters to help answering this question for a specific (a given species reared and processed in a given way to manufacture a given product) rather than a general scenario ("the" rearing of "the" insects). The review starts with providing a frame which consists of definitions (section Definitions) and an overview of how entomophagy has evolved and what the two major movements nowadays are (section Types of Entomophagy and Their Development), providing the bases to understand how this question can be answered. The seven key parameters are presented and discussed in section Factors Conditioning Food Safety and Sustainability of Edible Insects, while section Conclusion and Outlook contains conclusions and an outlook for future research needs.

[1]https://sdgs.un.org/2030agenda, last accessed on March 24th, 2021.

[2]https://ec.europa.eu/international-partnerships/sustainable-development-goals_en, last accessed on April 24th, 2021.

[3]Example https://time.com/5942290/eat-insects-save-planet/, last accessed on November 64th, 2021.

DEFINITIONS

Strictly speaking, an *insect* is defined zoologically, i.e., a six-legged arthropod with antennae, three pairs of legs, and the three-fold tagmatization (head, thorax, abdomen), in other words, a member of the class Insecta. However, in folk categories,[4] many other terrestrial arthropods are deemed to be insects (Costa Neto, 1999), such as spiders and scorpions (class Arachnida), centipedes (class Chilopoda), millipedes (class Diplopoda), and woodlice (class Crustacea). In this way, "insect" may refer to any terrestrial or freshwater arthropod that cannot be mistaken for a crustacean by people with no deeper knowledge of arthropods (e.g., crabs, shrimps, lobsters etc.).[5] This lack of accuracy is also seen in derived terms. *Entomophagy* refers to the insect consumption, regardless of the species that consumes them.[6]

Edible insects refer to those species with a known history of safe consumption, either traditional or non-traditional. *Mass-reared* or *productive insects* refer to insects reared for a specific purpose, e.g., foodstuff, feedstuff, industry, pest or waste management, pet arthropod trade etc. In this way, an edible insect can be, but does not have to be a productive species.

There are many definitions for "food," "food safety," and "sustainability." For this paper, the following definitions will be used:

Food: "[...] any substance or product, whether processed, partially processed or unprocessed, intended to be, or reasonably expected to be ingested by humans. 'Food' includes drink, chewing gum and any substance, including water, intentionally incorporated into the food during its manufacture, preparation or treatment." This definition was taken from Article 2 of Regulation (EC) 178/2002, but several similar definitions are accepted worldwide.

[4]Insect folk categories do not adhere to zoological ones as in many cases, all arthropods not identified clearly as crustaceans are seen as insects, e.g., also spiders, scorpions, ticks or woodlice (Costa Neto and Grabowski, 2021). Categories may be sympathetic (e.g., pollinator, spectacular looks, or honey production), antipathetic (annoying, stinging, food spoiling), or neutral. Societies engaging in traditional entomophagy have another folk category, "edible" which non-entomophagous societies lack.

[5]Yet, barnacles are taxonomically crustaceans but are not perceived as such.

[6]To be precise, the human food habit of consuming insects is "anthropoentomophagy" (Costa Neto and Ramos Elorduy, 2006). If other taxa are consumed, then correct terms would be "arthropoarachnophagy," "anthropochilopodophagy" etc. However, for the sake of simplicity, "entomophagy" will be used to refer to the consumption of the arthropods as perceived by the general public.

Informal food: "The informal food sector can be defined as including small producers, manufacturing enterprises, traders and service providers, involved in legal as well as unrecognized activities related to food" (FAO, 2007). Informal food providers particularly include farmers and hunter-gatherers.

Food safety: the sum of measures and concepts of handling, preparation, and storage of food in ways that prevent food-borne diseases (Sinell, 2003).

Food security: it exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."[7]

Sustainability: the ability to exist constantly (Kuhlman and Farrington, 2010).

Sustainable development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment Development, 1987). The 17 goals are no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, good jobs and economic growth, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption, climate action, life below water, life on land, peace, justice and strong institutions, and partnerships for the goals.

TYPES OF ENTOMOPHAGY AND THEIR DEVELOPMENT

Nowadays, there are two main movements in entomophagy, a traditional and a non-traditional one.

One is the *traditional entomophagy* that is global and, at the same time, as variable as the many species it refers to. Typically based on gathering the animals from the crops, the adjacent areas, and the wild on one side and traditional processing and consumption on the other side, this system has developed over the millennia on a trial and error base that enables it to (a) keep the resource available and (b) cope with the most important food safety risks. Consuming a certain insect species is a markedly local issue, determined by the species, its life cycle and availability as well as the cultural environment in which the given species is consumed, being accepted by the society to a high to low degree (Van Huis et al., 2013; Dobermann, 2017; Payne et al., 2019). For a more comprehensive look on the history of traditional entomophagy, see Payne et al. (2019).

As many items, food choice also depends on the surrounding culture. It may change when the culture does so, too. In countries in which European colonization (which at that time was non-entomophagous or even entomophobic in terms of food neophobia) toppled pre-colonial cultures (e.g., in many Latin American countries), keeping up traditional food habits was frequently associated with marginalized people or ethnic groups of that country in terms of being poor, with little education, and retrograde. In those cases, entomophagy was either not taken seriously or even discouraged (Ramos Elorduy and Pino Moreno, 1989). Though sometimes reduced in terms of actual consumers, entomophagy simply existed. It was mostly left unattended by local policy-makers being treated as an "informal foodstuff" (see definition in section Definitions). The presumed reasons for this may be numerous. In societies where entomophagy is a habit accepted by the mainstream (e.g., in many Asian countries), people have been eating insects from their childhood on and may not have questioned it. This will typically be the case when food-related risks were small enough not to require any further attention.

The other main movement is non-traditional entomophagy. Rather than producing and consuming edible insects as done for millennia, this term includes both the modernization of parts of traditional entomophagy (e.g., cricket farming, modern hygiene concepts etc.) and the building of a completely new agricultural branch with "new" species like e.g., darkling beetles (Tenebrionidae spp.) and flies like the black soldier fly (*Hermetia illucens*) or the housefly (*Musca domestica*). It originated outside the traditional entomophagous societies and, in terms of knowledge generation and propagation, its bases lie in science. However, the driving force is the market, as any other modern agribusiness.

Scientific approaches to entomophagy started in the area of ethnozoology, recording which ethnic group consumed which insect species in which context, which goes together with discovering insect biodiversity as such (e.g., Meyer-Rochow, 1975, 2005; Costa Neto and Ramos Elorduy, 2006; Dawwrueng et al., 2017). Many people with a Western point of view regarded insects as a food curiosity of supposedly poor and uneducated tribes, though, conserving this twentieth century attitude toward entomophagy up to now. In the last decades of the previous century, more information beyond anthropology was published, e.g., nutritious values (e.g., Ramos Elorduy and Pino Moreno, 1989). While science can be pure theory, actual consumption of insects outside the traditional entomophagous societies (and those visiting them) started in same time, with entomologists organizing tasting events (Payne et al., 2019). In this way, the benefits of consuming insects also in countries without an entomophagous tradition are nothing new of the twenty-first century. However and based on these publications, the FAO and an international group of scientists (Van Huis et al., 2013) corrected this image. Edible insects are one of several ways to combat hunger and address the climate change on a global base. In addition, the potential of mass-produced insects as bio converters to break down significant quantities of food waste under controlled conditions was also recognized. In 2012, the UN FAO held an expert consultation to explore this topic and published a resulting report titled "Assessing the Potential of Insects as Food and Feed in Assuring Food Security."[8] Based on this, a conference titled "International Conference Insects to Feed the World" was launched in 2014. This congress was the "big bang," particularly for many of the stakeholders currently involved in the growing variety of areas of

[7] http://www.fao.org/3/w3548e/w3548e00.htm, accessed last on April 28th, 2021.

[8] http://www.fao.org/publications/card/en/c/0a1987d0-458a-59bf-a2b2-c38687aaeba7, last accessed on April 26th, 2021.

insect production. After that, interest in the subject has increased almost exponentially. To give an example, when consulting NCBI, the National Center for Biotechnology Information[9] for *H. illucens*, the black soldier fly, by publication year, a total of 22 papers were published between 1800 and 2013. In 2014, there were 10, 14 in 2015, 13 in 2016, 42 in 20017, 51 in 2018, 136 in 2019, and 223 in 2020, showing the growing interest of science in productive insects. Payne et al. (2019) provide a deeper insight into the development of what they call the "entomophagy movement" and the role the media, the researchers, the entrepreneurs and the legislative power play in Europe, the US and Canada in that context.

Non-traditional entomophagy is aimed toward (a) improving traditional entomophagy and (b) extending entomophagy to non-entomophagous societies.

Regarding the first aim, traditional methods used so far have been efficient to ensure sustainability and food safety within the local range and conditions where they have been applied. Those not meeting these criteria are likely to have been abandoned. However, these conditions have changed over the years and may not address modern challenges, and modern(ized) approaches are starting to get developed, as will be detailed in section Factors Conditioning Food Safety and Sustainability of Edible Insects.

Regarding the second aim, non-traditional approaches substitute gathering by harvesting insects from farms as mini-livestock (in consideration of the ecological knowledge that has been accumulated over the last decades), employs also modern processing techniques and preferably works with homogenates (meals, purée) to overcome the disgust many people outside the tradition experience when thinking about insects.[10] Apart from using whole animals, insects can also be processed to extract certain substances, particularly proteins and fats (Smetana et al., 2016, insect biomass) and other substances, as food and feed, pharmaceuticals, biofuels, and lubricants.

However, the distinction is not made so easily. Farming has also been a traditional method to produce insects. The best-known example is sericulture, practiced for more than 5.000 years, yielding silk and, as a by-product, the edible pupae (Barber, 1992). Sericulture is also practiced outside Asia, and other species have the potential for rearing in order to produce both silk and food, e.g., the endemic silkworm *Borocera cajani* from Madagascar, a lasiocombid eggar. Beekeeping is even older (Roffet-Salque et al., 2015) and has been practiced in both the old (honeybees) and new world (stingless bees) species. Sustainable farming techniques have also been recorded for other species. In Mexico, the Nahua have been managing ant (*Liometopum apiculatum* and *L. occidentale*) nests for centuries to harvest ant larvae and pupae (*āzcamolli*, "escamole" in modern Mexican Spanish), which are consumed as a high-price delicatessen. This technique, called *texalātzcatetlātehmolo* ("gathering sandy stone ants among the rocks"), comprises digging out an ant nest, opening it, shaking the larvae out onto a cloth, closing the nest, and replacing it thoroughly (López Ávila, 1991). In Japan, *Vespula* spp. wasp nests found at an early stage of development are also attended and harvested afterwards (Nonaka, 2010). Hence, farming is not an exclusively modern approach to manage edible insects.

[9]https://www.ncbi.nlm.nih.gov/, last accessed on March 18th, 2021.

[10]In this way, insects are an extremely susceptible subject which is more connected with fear and disgust than other "novel" productive species ("novel" in this case is novel in the Western cultures), e.g., ratites, camelids, or algae, with novel plant products being more easy to accept than novel animal species. The reasons for this entomophobia seem multiple, and a deeper analysis of this condition would exceed the frame given here. Another way to overcome food neophobia is by information.

FACTORS CONDITIONING FOOD SAFETY AND SUSTAINABILITY OF EDIBLE INSECTS

The actual consumption of a given foodstuff is the balance of a series of factors that either promote or discourage it. The same is true for food safety and sustainability. For edible insects, the following factors will be revised:

1. Biology of the species
2. Level of knowledge of the foodstuff
3. Traditional knowledge
4. Efficiency of traditional methods given the societal changes and needs
5. Farming conditions
6. Actual processing, transport, and storage
7. Consumer awareness and acceptance.

However, these factors are not unique for insects but rather for every foodstuff. Still, they assemble in a unique, foodstuff-specific manner, as some aspects may be more important than others under given conditions. In the following it will be reviewed what should be considered in the case of edible insects.

Biology of the Species

Ethnobiology recognizes between 2,000 and 3,000 species of edible insects (Mitsuhashi, 2016), the precise number being disputed within the scope of insect taxonomy. Currently, the most accepted list is that one published online by the University of Wageningen (The Netherlands).[11] Apart from insects, the list also contains some other terrestrial arthropods like spiders and scorpions.

The striking feature is the sheer amount of species known to be edible. It cannot be matched by vertebrates, neither domesticated nor caught in the wild (**Table 1**).

These species cover almost all insect orders, although beetles (Coleoptera), butterflies and moths (Lepidoptera), bees, wasps, ants etc. (Hymenoptera) contribute most species. These are holometabolous taxa (i.e., immatures do not resemble adults and they have a pupal stage), and the instars typically—but by far not exclusively—consumed are larvae and pupae. Hemimetabolous insects (immatures do resemble adults, and there is no pupation) like crickets, grasshoppers and locusts (Orthoptera), bugs (Hemiptera), and termites (Isoptera) may contribute less species, but among them are groups that are consumed on a broader scale (Van Huis et al., 2013).

[11]https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm, last accessed on April 20th, 2021.

TABLE 1 | List of vertebrate species [*n*; estimated] used as a foodstuff worldwide[a].

Taxon	Domestic species (*sensu lato**)	Game, fishery, wild harvest species
Even-toed ungulates	15+	200+
Other mammals	4+	200+
Birds	25+	200+
Reptiles	10+	80+
Amphibians	5+	100+
Fish	80+	200+
Total	**139+**	**980+**

*(semi)domesticated, tame, and undomesticated but bred in captivity regularly.
[a]https://en.wikipedia.org/wiki/List_of_domesticated_animals.

TABLE 2 | Examples for edible insects not meeting the requirement for the "ideal food insect" (based on Harwood and James, 1987; Menzel and D'Aluisio, 1998; Costa Neto and Ramos Elorduy, 2006; Loiácono and Margaría, 2010; Van Huis et al., 2013; Grabowski, 2017).

Criterion	Examples
Size	Ant eggs are very small.
Large amounts	Many large beetle grubs live a solitary life.
Manageable toxins	Sphinx moth caterpillars may still be toxic after cooking.
Physical damage	Water bugs may sting at the moment of capture, some caterpillars are covered with urticating bristles, Asian giant hornets (*Vespa mandarinia japonica*) may deliver deadly stings.
Disease transmission	Many insects contain microorganisms that are opportunistic pathogens, edible bot-flies are harvested from infested caribous.
Hygiene	Storing insects in humid tropics is difficult.
Nutrition	The nutritious value of insects depends strongly on the species and the feeding regime.
Taste	The taste varies with the species.
Culture	The Muslim and Jewish food laws only accept locusts as edible
Price	Crickets in Thailand are sold for less money than giant water bugs.

As all living beings, insects occupy certain niches within their environment. Triggered by evolution, each life cycle is the result of genetic bases and the challenges that the environment poses to the species, making virtually each species unique in its biology. Essentially, vertebrate species are subjected to the same pressure, but the sheer amount of edible insect species is the primordial reason for which the question posed in this contribution's title was answered with "jein."

Handling living or dead insects may be risky. Some insects can transmit diseases or cause intoxications, allergies, and physical injury (see below). In some cases, these hazards are combined, e.g., a poisonous sting or a bite transmitting a pathogen. Traditional selection of edible insects is a complex matter, governed by trial and error, but also by cultural aspects. The "ideal" edible insect is large, appears in large amounts, is not toxic resp. its toxins may be controlled by cutting off the toxic body parts or by inactivating the (thermolabile) toxin by heating, does not cause avoidable physical damage (e.g., thorns, bites, stings etc.), can be harvested readily and safely without major risks for the operator, does not transmit diseases, can be processed into a hygienic foodstuff, can be stored without major quality changes, is nutritious, tastes good, sells at a good price, and is culturally accepted, i.e., there are no food taboos or disgust feelings associated with it.

This list may not be complete, and many edible insects may not meet all requirements, as the examples in **Table 2** show.

In this way, each species yields an individual profile of suitability.

Each species has a life cycle of its own. Be it hemimetabolous or holometabolous, the life cycle starts with the eggs, passes through several immature stages (nymphs or larvae and pupae) and ends in the imago (plural imagines), the sexually mature adult. It is mandatory to know the life cycle because, on one hand, consumption may be limited to certain phases (instars). While most edible beetles, butterflies and hymenopterans (ants, wasps, bees etc.) are consumed as immature instars, imagines are rarely eaten because they can either sting (hymenopterans), be toxic (e.g., mealworm imagines) or simply have a strong exoskeleton that makes chewing more difficult. Legs and wings may be trimmed, but insects are not peeled traditionally (Menzel and D'Aluisio, 1998; Grabowski, 2017).

On the other hand, knowing the life cycle is also a fundamental aspect of farming efforts (Tchibozo et al., 2016). The marked difference between the traditionally "available" and the non-traditionally species that are suitable for farming (**Table 1**) is not only due to the centuries of experience between these two production systems. Although the amount of farmed insect species will rise in the future, not all edible species can be farmed sustainably due to the idiosyncrasies of their life cycles. As insects are perfectly adapted to an ecological niche that can be small or large (Honomichl, 2003), and so is their adaptability to farming conditions, successful rearing means the effective provision of elements necessary to pass through all phases of the life cycle. In this way, there can be constraints in the fitness for farming (**Table 3**), making the management more or less sustainable.

Hence, farming them like crickets or mealworms is prone to be not sustainable. However, other concepts may be more efficient, e.g., managing edible insects as one of many resources of a determined area, e.g., for forestry (Nonaka, 2010).

Finally, rearing the animals must comply with the legal framework in the corresponding country (Grabowski et al., 2020). This is why some crickets (*Acheta domesticus*, *Gryllodes sigillatus*, *Gryllus assimilis/locorojo*, and *G. bimaculatus*), locusts (*Locusta migratoria* and *Schistocerca gregaria*), darkling beetles (*Alphitobius diaperinus*, *Tenebrio molitor*, and *Zophobas atratus*), and even flies (*H. illucens* and *M. domestica*) have become increasingly popular as productive insects, as they fulfill many of these requirements. However, this "international" list is growing constantly with species that acquire local importance, e.g., the Asian crickets *Gymnogryllus vietnamensis*

TABLE 3 | Fitness for farming constraints potentially associated with the edible insect's life cycle.

Constraint	Examples
Be too long	Longhorn beetle grubs are consumed worldwide. However, their life cycle takes up to 10 years to complete (Kariyanna et al., 2017).
Require too much space	Cicadas are also popular. Their life cycle comprises several nymphal instars which are passed underground, feeding on tree roots in a depth of up to three meters. Besides, the life cycle can also take up to 17 years (Marshall, 2001). Another aspect is territoriality. Defending its territory has been documented in many insect taxa decades ago (Fitzpatrick and Wellington, 1983).
Can only be carried out partly in captivity	Juvenile dragonflies can be reared in aquaculture, while adult specimens require not only a vast territory for hunting but also specific ponds or rivers for oviposition (Honomichl, 2003) which will make controlling the entire life cycle very costly.
Be too challenging in terms of providing feed	Many insects are oligo or even monophagous (Cates, 1980), making the completion of the life cycle highly dependent on the correct feedstuff resp. limiting the farming to those areas where this feedstuff can be produced sustainably. Sericulture is a notable exception to the rule.
May be too risky for the environment	Many pest insects are edible which at first glance seems a good way to control pests. Depending on the species, farming them without diligent biosecurity concepts to avoid escapes may be too risky. Palm weevil grubs (*Rhynchophorus* spp.) are popular in Asia, and xyloculture (the grubs feed on important crop palm species) has been developed (Hanboonsong et al., 2013). Escaping weevils in a palm-growing area would be a serious threat to the farmers. Some countries are so strongly affected by this pest species that there are laws to combat them (Grabowski et al., 2020). The same is true for any species reared in a foreign country in which the species would be a neozoon that could have ecological impacts.

and *Teleogryllus mitratus*, the Mexican grasshoppers known as *chapulines* (*Sphenarium* spp.), stingless bees in Latin America (tribe Meliponini) or the African bush cricket *Ruspolia differens*. Still, it should be stressed that the "international" species seem to have originated from the pet food sector and by chance also resulted suitable for human consumption (Costa Neto and Ramos Elorduy, 2006; Grabowski, 2017; Van Huis, 2020; Magara et al., 2021). Locusts, such as migratory (*L. migratoria*) and desert (*S. gregaria*) locusts are traditionally mostly consumed in times of invasion when swarms offer a large amount of available insects. These crop pests can then be both a source of food for the family and a source of significant income (Tchibozo and Lecoq, 2017).

Level of Knowledge of the Foodstuff

Knowledge of edible insects has two main sources: traditional knowledge acquired by centuries of trial and error and transmitted from one tradition to the next, and results from scientific research, either gathering field data of traditional knowledge, or creating genuine new data by experiments and sample analysis. With insect farming, a third source has started to form: practical experiences made while rearing.

Knowledge on edible insects is dynamic and highly species-dependent. **Table 4** presents the hits when consulting the National Center for Biotechnology Information (NCBI) platform[12] with the keywords "edible" and the scientific name of a given insect. In this, the results for the "international" list cited above is compared with those of a randomly chosen page of the Wageningen list[13] (page 17). Since a positive hit can be any publication that contains the keywords in any kind of relation, only subject-related hits (i.e., referring to consuming the insect) are presented. Comparing the number of species to the positive hits it becomes clear that for most of the edible insects, information is rather poor, while it's only the "international" species for which a detailed knowledge has been created.

This does not mean that these "minor" species could not be as efficient (or even more efficient) in terms of sustainable management. It simply requires more research.

Traditional Knowledge

As mentioned before, traditional knowledge is intended to subsume the experiences accumulated over time (Musundire et al., 2021). Depending on the country, literacy can still go down to 20%.[14] Besides, ∼25% of languages have no own writing system, making oral information transmission obligatory. As mentioned in the introduction, recording the food habits of the different ethnic groups was the initial step toward non-traditional entomophagy. Globalization stands for modern life and welfare, and is one of the reasons why oral tradition may become interrupted between generations (Fangjun, 2009). In Benin, entomophagy is seen as "backwards" and often discontinued when moving to a larger city (Riggi et al., 2013). As a consequence, information is lost, possibly even lost before recorded and publicly available. This also applies to food habits. In the worst case scenario, the wheel has literally to be reinvented to regain this knowledge. This, however, is again a locally dependent phenomenon, influenced by the general status insect consumption has. As a counter-example, entomophagy is a common practice in Thailand and Cambodia, and consumption occurs in rural and urban areas alike. In fact, moving to other Thai provinces within the country increased entomophagy by accepting local species.[15]

Traditional knowledge is by far not complete, i.e., it does not subsume all there is to know about a given species in a given area, as can be seen by comparing natural ranges of insects with the records attesting traditional entomophagy. Some of the Haitian pest insects (recorded as early as Smith and Audant, 1928) are

[12] https://www.ncbi.nlm.nih.gov/, last accessed on April 20th, 2021.

[13] https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm, last accessed on April 20th, 2021.

[14] https://ourworldindata.org/grapher/literacy-rates-most-recent, last accessed on April 20th, 2021.

[15] Mitchaothai and Lertpatarakomol, personal communication 2021.

TABLE 4 | Subject-related hits [*n*] for several edible insects at NCBI (see text for details).

List	Order	Family	Genus, species	Hits
International	Orthoptera	Acrididae	*Locusta migratoria, Schistocerca gregaria*	92
		Gryllidae	*Acheta domesticus, Gryllodes sigillatus. Gryllus assimilis, G. bimaculatus*	207
	Coleoptera	Tenebrionidae	*Alphitobius diaperinus, Tenebrio molitor, Zophobas atratus*	263
	Diptera	Muscidae	*Musca domestica*	20
		Stratiomyidae	*Hermetia illucens*	237
Wageningen (p. 17)	Lepidoptera	Saturniidae	*Pseudobunaea* spp., *Rohaniella pygmaea, Saturnia* spp., *Tagoropsis* spp., *T. flavinata, T. natalensis, Urota sinope, Usta terpsichore, U. wallengrennii*	16
		Sphingidae	*Acherontia atropos, Agrius convolvuli, Coelonia fulvinotata, Hippotion* spp., *H. eson, Lophostethus dumolinii, Nephela comma, Platysphinx stigmatica, Trithermis arteriosa,* Sphingidae gen.	17
	Odonata	Odonata fam.	Odonata spp.	27
	Orthoptera	Acrididae	*Acanthacris ruficornis*	1

edible, e.g., the paper wasp *Polistes crinitus* and the cockchafer *Phyllophaga hogardi*. Still, there is no record of consumption for that country, either because it exists but was not recorded or not practiced at all.

Thus, there are two contradictory developments regarding entomophagy knowledge. Traditional knowledge exists, but the degree of transmission varies with the region and may be supported by recording them for publication. While traditional knowledge may be endangered, scientific evidence is created at an increasing speed, but may not be considered as a base to start from.

Traditional insect processing is as diverse as the species. Mutungi et al. (2019) list 45 species × processing combinations for food insects just for Africa. Their safety and sustainability will depend largely on the specifics of the methods and the skill they are performed with.

However, due to ethnocentric reasons, since food insects are not considered appropriately "mainstream" in dominant Western cultures, there has been a tendency to ignore or omit the relevance that edible insects have to other cultures. Often, only indigenous or generic names are known, making it difficult to know which species they belong to. Therefore, it is necessary for researchers to conduct studies using an interdisciplinary approach paying attention to the values and knowledge of traditional peoples (Costa Neto and Dunkel, 2016).

The potential of insects as food represents an important contribution to the debate of biodiversity, as it opens a perspective for economic and cultural valuation of animals usually considered "useless" for the human. Wild-caught insects are one of the wild foods (Bharucha and Pretty, 2010). Wild foods in informal food systems are estimated to contribute to the daily diet of about 1 billion people worldwide (Aberoumand, 2009), and to diversify daily diets and livelihood strategies in developing countries (Bharucha and Pretty, 2010). It is therefore necessary to safeguard and enhance this traditional knowledge (Costa Neto, 2002; Tchibozo and Lecoq, 2017).

Efficiency of Traditional Methods in View of Societal Changes and Needs

Another dimension of complexity is added when the degree of efficiency of traditional methods is considered. **Figure 1** depicts the three major aspects of practical, traditional entomophagy. While the species selection was discussed already, resource management is typically achieved by limiting the access of consumers to the resource (Meyer-Rochow, 2005; Riggi et al., 2013). A typical way to do this is by putting food taboos, e.g., allowing a given species only for a certain sector of the population, e.g., pregnant women, small children, seniors etc. These limitations do not apply to those species which are (temporarily) abundant like locusts, cicadas or certain caterpillars like the mopane worm (*Gonimbrasia belina*), but rather to those that are not as frequent.

Ensuring food safety is mainly achieved by heating steps, e.g., by cooking, roasting or (deep-)frying. However, some insects are also traditionally consumed raw, but this applies only to a subset of the total array of consumed insects in a given area. This suggests that also raw consumption was evaluated over the centuries and deemed feasible, while for other species, heating is still considered necessary (Menzel and D'Aluisio, 1998; Grabowski, 2017).

Another frequent measure is managing the intestinal content. In Mexico, fresh-caught grasshoppers are left for 1 day to fast so to empty the digestive tract as the folk opinion is that a filled gut leads to a bitter taste. In southern Algeria, to cure several diseases, the popular tradition is to eat desert locusts (*S. gregaria*) without emptying their digestive tract which may contain several species of medicinal plants. Other methods to cope with this on global level is degutting (e.g., squeezing out caterpillar intestines) and feeding insects "tastier" feedstuffs before killing them, e.g., fruits, vegetables, or cereals. It was thought that this method also reduced bacterial loads of the animals, but this could not be corroborated (Klunder et al., 2012).

In this way, traditional control methods address traditional food-related problems. However, problems may come from two different sources.

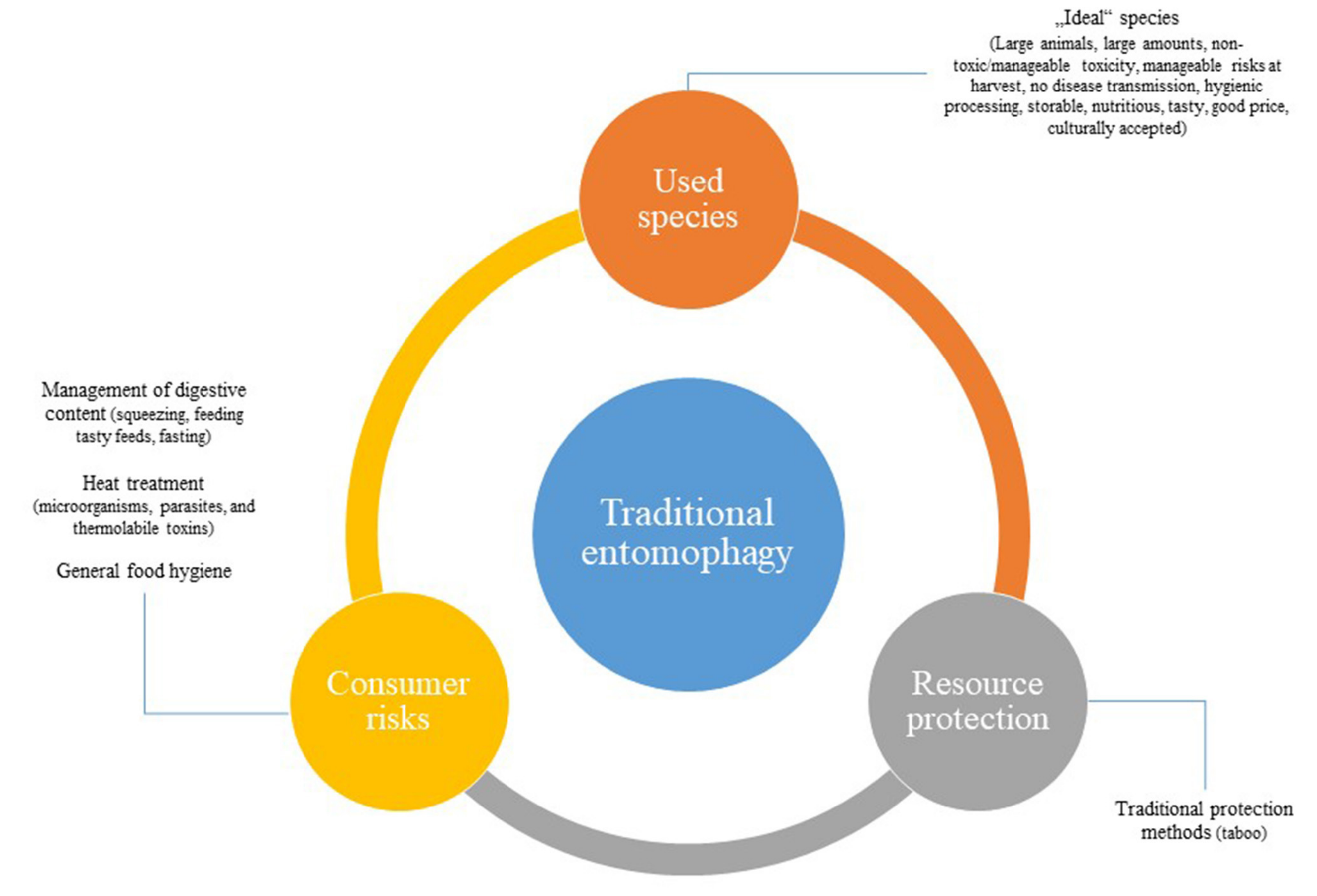

FIGURE 1 | Traditional entomophagy.

First, these methods may already have a longer history of inefficiency. One typical example is selling trimmed insects on markets, i.e., insects in which some body parts were removed, e.g., legs or wings. Under physiological conditions, an insect is colonized by microorganisms on the outside, in the intestinal tract and in the tracheae, but there are anatomic barriers to prevent the animals' inner tissues to become infected. When insects are trimmed, these barriers are destroyed, so that bacteria contaminate the tissues beneath them (Grabowski, 2017). This problem was seen e.g., in the East African katydid *Ruspolia nitidula* called *nsenene* in Luganda, where traditional trimming includes wings, legs, and even antennae. They must be processed quickly (sautéing and drying) to ensure a proper shelf life. However, when transport is delayed, the quality (defined as sensorial, chemical, and microbiological stability) dropped (Ssepuuya et al., 2017). Barriers are also lost when insects are dried and milled, also leading to elevated microbial counts when heating was ineffective. As the microbiome is strongly influenced by the species, so is its reaction to heat treatment, but spore-forming bacteria and staphylococci usually increase during drying (Grabowski and Klein, 2016).

The second kind of problem arises when traditional conditions in which using the insect resource developed change. These changes can occur all along the production chain and affect primary production (insect feed contamination), processing and storage (e.g., in plastic bags instead of baskets). Climate-related shifts in the microbiome also enter in this section; as the temperatures rise in some regions, traditional preservation methods adapted to more moderate temperatures may fail. While bacterial risks can be controlled by heating and preventing secondary or re-infections, non-traditional toxins (contaminants) are not considered in traditional risk prevention systems, simply because they are relatively recent. Insects can take up and carry over many ambient contaminants which may pose a risk for the consumer, e.g., heavy metals or pesticides (Hanboonsong et al., 2013; Mutungi et al., 2019).

Farming Conditions

Insect farming is regarded one of the modern ways to make use of insects. There are clear advantages over gathering. First, natural populations are protected. Ecological awareness lead to understanding insects as integral part of food webs in which they act in many different manners (carnivores, herbivores, decomposers). Removing these insects from the webs causes imbalances, depending on the role the insect species has (Kormondy, 1996). Second, the production can be controlled

TABLE 5 | Main insect farming systems, classified according to environment conditions (Grabowski, 2017).

Type	Housing conditions	Examples
Xiroculture	Animals reared on dry substrates, e.g., dry containers, egg carton, dry cereal products	Crickets, locusts, mealworms, adult flies
Hygroculture	Animals reared on a humid environment, e.g., decomposing plant and animal-based feeds	Fly maggots
Aquaculture	Animals reared in tanks or ponds, sometimes with a bank section to create semi-aquatic conditions	water beetles, water bugs
Xyloculture	Wood and palm tree consuming species reared inside their host plants (living plants, cut logs or containers filled with wood shaving or sawdust)	Weevils, ants, bamboo borers

and manipulated. This is particularly important for feeding, as the farmer can select feedstuffs that are free of contaminants. The farmer may also choose side-streams for waste management, making farming more sustainable.

Farming is suitable for some, but not all edible species due to life cycle constraints (see section Biology of the Species). In relation to basic environment conditions, insect farming techniques can be categorized into four main systems (**Table 5**). Other classifications would be according to space (extensive, intensive etc.) or feed type. For each system, special challenges may occur that must be addressed. Microbiological analyses of frass samples of one of the authors' insect rearing units showed that *E. coli* was present in hygroculture, but absent in xiroculture, although both systems were operated in the same room.[16]

Depending on the life cycle, combinations of farming systems may be handy. To give an example of this kind of combinations, young black soldier fly larvae (*H. illucens*) grow better in a humid environment (hygroculture), while post-feeding larvae actively search for a dry environment (xiroculture; Dortmans et al., 2017). In recent years, manuals have been edited for more common species (e.g., Dortmans et al., 2017; Hanboonsong and Durst, 2020; Phalla and Chhay, 2020), but also for those with local importance, e.g., Kayikananta (1997) or Samnák Phim Màebaan (ed.) (2015) for Thai species.

Insect farming can be also seen at the large, medium and small scale depending on biomass produced or the insect company's main objective. First, big multinationals produce insects on a large scale (high insect biomass/day). Second, micro-enterprises produce insects offered at the local level due to the use of simple technologies. Third, small-scale farmers for whom insects are also highly suited, rear this species with important social benefits and income generation opportunities (Chia et al., 2019; Barragán Fonseca et al., 2020).

Sustainable insect farming is basically possible (Berggren et al., 2019; Guiné et al., 2021). The 17 goals of sustainable development are met, either directly (no poverty, zero hunger, good health and well-being, good jobs and economic growth, gender equality, reduced inequalities, innovation and infrastructure, sustainable cities and communities, responsible consumption, climate action, life below water, life on land, and partnerships for the goals) or indirectly (quality education, clean water and sanitation, affordable and clean energy, and strong institutions; Dicke, 2018). An interesting case is sustainable development 16 (peace and justice), which can be focused on restoring food production by smallholder farmers, improving their socio-economic position as it has been seen in the international initiative "Insects for Peace" (Barragán Fonseca et al., 2020). Insect farming is particularly interesting to address gender-based inequalities as in many parts of the world, women are typically engaged in farming activities and extra income does not only strengthen the family economy and nutrition, but also empowers women. The ongoing project IFNext[17] performed by some of this review's authors in Cambodia and Thailand where women farming crickets (*G. bimaculatus, G. assimilis,* and *G. vietnamensis*) and silkworms (*Bombyx mori*) has increased their income and supply with nutrients. Cricket farmers also use local vegetation as feedstuff, of which some are invasive species, contributing thus to their control (Phalla and Chhay, 2020).

Another aspect of sustainability is efficient use of resources. In terms of insect feeding, two major approaches are possible. One is the focus on insect product quality. Like any other living organism, insects transform feed into energy and body tissues. The precise output will depend largely on the feedstuffs, leading to marked compositional differences described in the literature. The amount of publications regarding this subject has increased noticeably over the last years, leading to an increased understanding of how feeding management affects the quality of the insect product. Thus, it is possible to produce insects with a stable composition. However, this is based on a stable quality of the feedstuff, and if the latter is not available, it must be supplied by other feedstuffs following a cautious nutrient calculation. Eventually, feedstuffs must be purchased at higher prices to meet the own quality standards. This approach is recommended when products are sold to major companies.

The other is the focus on feedstuff availability. Insect farming is very attractive to small and medium-sized farmers. As they do not always have the financial means to buy a feedstuff at any price, they switch to use whatever is (a) available and (b) consumed by the insects. This keeps production costs low, but can lead to a lower resp. changing nutrient quality. This may sound difficult to manage for companies that buy insects for further processing at the first glance, but many foodstuffs arrive at processing plants in varying chemical composition, e.g., raw milk, which is not only heat-treated but also fat-corrected before processing. This approach is therefore suitable for small and medium farmers and companies that can cope with compositional variations and for those selling whole insects as food to the end user.

[16]This is obviously due to the enviornmental factors that affect the growth of *E. coli*.

[17]https://www.tiho-hannover.de/kliniken-institute/institute/institut-fuer-lebensmittelqualitaet-und-sicherheit/arbeitsgruppen/nutzinsekten/forschung-ifnext, accessed last on April 21st, 2021.

Sustainability assessment is a complex matter as many factors need to be considered, and actual assessments must be carried out by a multidisciplinary team (Berggren et al., 2019; Guiné et al., 2021). To cite only some of these professions to assist a farmer, entomologists are familiar with species and the life cycles, livestock veterinarians are experts in adapting them to farming conditions, observing animal health and animal welfare, feed experts keep nutrition in mind, physicians assess the health of the operators, agricultural economists monitor the costs, ecologists assess the impact of the farm, and economists evaluate the market. This large amount of professionals is impractical for an ordinary farm, moreover if the farm is small, but is necessary for any larger and comprehensive research. In the future, however, a partnership between farmer and veterinarian is the goal, just as with ordinary livestock.

Safety may refer to animal health and welfare, operator health and product safety. On one side, farming is a safe practice as the farmer is in charge and controls all operational steps. Being able to control and manipulate the feeding is a vital aspect of food safety, especially in the case of toxicological risks. On the other side, each labor also yields risks for the operator. Regarding infections, most insect pathogens do not affect humans because of the large taxonomic difference between these groups. However, some bacteria and fungi and even parasites do, and insects can act as vectors for typical food-borne diseases like salmonellosis (Jeandron et al., 2011; Grabowski, 2017). Insect farmers may also be affected by dusts created while farming toward which they can develop allergies (Perlman, 1958; Liebers et al., 1993; Garino et al., 2019), in addition to ordinary risks. Animal welfare will be addressed in section Consumer Awareness and Acceptance.

Actual Processing, Transport, and Storage

After primary production, the subsequent stages of manufacture until the product reaches the final consumer are subsumed in this section. Food safety and sustainably may also be affected at these stages. Whenever a foodstuff becomes unsafe and must be discarded, sustainability is compromised, as efforts to produce a foodstuff were in vain, and ways to eliminate these unsafe foods can be energy-consuming and/or result in pollution. However, there are also sustainable ways to dispose of unfit foods, e.g., bio gas generation, that would mitigate the impact on sustainability.

Food safety has been a concern worldwide since non-traditional entomophagy commenced. The European Food Safety Authority (EFSA[18]) published a scientific opinion, subsuming what was known on the matter and evaluating the known risks. At that time, the EFSA concluded that eating insects poses no bigger risks than consuming more conventional foodstuffs. While biological risks can be handled *via* hygiene and proper processing, the chemical ones can be managed by a control of the feedstuff for the insects which is best done at farming.

In 2021, two species of so-called "novel food" insects have been officially authorized as a foodstuff in the EU, the yellow mealworm (*T. molitor*) and the European migratory locust (*L. migratoria*). Before recognition, corresponding scientific opinions were published[19] stating that consuming them within the specifications as established by the applicants, there are no major safety concerns, but stressing that in both cases, a primary sensitization and cross-reactions are possible. This means that consumers may become allergic to insects or those allergic to other arthropods may also show allergic reactions. Eventually, these two species were integrated into the EU novel food catalog[20]. Specifications refer to the uses (product type and allowed percentage of insects) and the properties (chemical compositional, microbiology, and contaminants), along with the need to refer to their allergenicity on the labels.

Traditional processing and its varying degree of sustainability and food safety were already discussed. Modern processing may also use traditional methods such as heating or drying. It is estimated that in the future, most consumers will have a non-traditional background (see below), which goes along with a certain degree of reluctance to consume insects that can be identified visibly as such. In reply to that, modern techniques rely on dissolving the insect shape and use homogenates, sometimes only extracts (Collins et al., 2019). This technology has increased markedly over the years as seen by the number of patent applications in this sector (Kim et al., 2019).

These advanced technologies have been applied successfully in more conventional foodstuffs, and it is only logical to submit insects to similar treatments. However, to guarantee operational and hygienic processing, all the requirements used in other food technology devices must be met, making at least this part not as sustainable as the primary production due to energy requirement and supply of material necessary to elaborate the complex machinery (Knorr and Watzke, 2019). Besides, health risks may arise during processing as seen in many foodstuffs (discussed e.g., in Virk-Baker et al., 2014).

Post-primary production also includes transport and storage. In this way, insect products face the same challenges as other foodstuffs (Ferri et al., 2019). It is beyond questioning that shipping any foodstuff between continents is a stress test for food safety which can be met with appropriate measures such as cooling etc. This reinforces food safety, but reduces food sustainability. Besides, the amount of food lost between primary production and retail is ∼25%, affecting environmental sustainability (FAO, 2019).

Storage is another factor that may affect sustainability and food safety. Storing food at ambient temperatures is less energy-consuming than cooling or freezing. However, dried insect products may yield high bacterial counts (see above), may be subjected to rancidness and can be hygroscopic, enhancing microbial growth even further due to a_w value changes (Grabowski, 2017; Mutungi et al., 2019). Even heated insects may pose a risk as an outbreak of histaminosis in Thailand demonstrated (Chomchai and Chomchai, 2018).

[18]https://www.efsa.europa.eu/de/efsajournal/pub/4257, accessed last on April 22nd, 2021.

[19]https://www.efsa.europa.eu/en/efsajournal/pub/6343 and https://www.efsa.europa.eu/en/efsajournal/pub/6667, accessed last on November 25th, 2021.

[20]https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R0882&qid=1637841369164&from=DE and https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R1975&qid=1637841488217&from=DE, accessed last on November 25th, 2021.

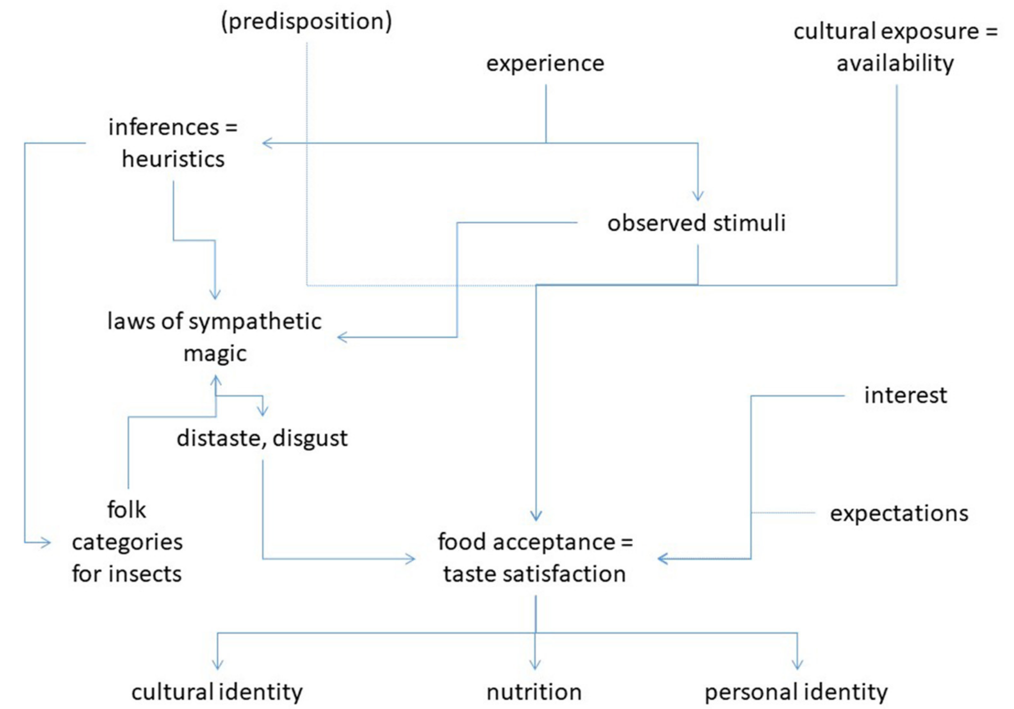

FIGURE 2 | Food acceptance (from Grabowski, 2017). See text above for a detailed explanation.

Consumer Awareness and Acceptance

The role of the consumer is the final factor that justifies the idea of producing insect-based foodstuffs or not. A food can be as safe and sustainable as can be, but the effort in producing it is futile when the consumer simply does not eat it. Naturally, the latter is more likely when the consumer lacks a traditional entomophagy background. Food safety and sustainability are typical requirements Western consumers have when it comes down to foods which are new for them (Dagevos, 2021).

The main goal to consume food is obviously nutrition, but food choices are also a sign of personal and cultural identity. Food acceptance is another complex process in which an individual decides what to eat and what not to eat (**Figure 2**). Based on experience and local availability, a known foodstuff is recognized and evaluated for freshness before actual consumption. In traditional entomophagy, consumers eat insects mainly because of the taste (Menzel and D'Aluisio, 1998) and treat them as ordinary foodstuffs. Of course, not all consumers in entomophagous societies actually do consume insects, just as people in non-entomophagous societies do not consume all ordinary foodstuffs, neither. There are preferences, even among insects, and consumers have explanations for both preferences and avoidances. To give an example regarding whole insect consumption, German consumers put to the test preferred crickets ("they are not so big") or avoided them ("they look like spiders"). The same happened with locusts ("a good mouthful" vs. "far too big") and mealworms ("they do not look like insects" vs. "they look like worms"). Some Cambodian consumers have no problem in consuming crickets or locusts, but do not eat giant water bugs as they are perceived as being too big.[21]

When an unknown foodstuff is presented, heuristics is applied, i.e., an educated guess if it is edible or not, comparing the item with things the individual already made experiences with. Of course insects are known items. As all animals, insects are placed into different folk categories (see section Definitions), and if the species does not fall into the positively associated ones (e.g., honeybees), reluctance emerges. This is particularly the case in non-entomophagous societies that, in contrast to the entomophagous ones, lack the folk category "edible." If the educational and/or cultural background linked the presented food insects with disgust or distaste, the laws of sympathetic magic will reduce the willingness to taste.[22]

Reasons for rejecting edible insects have been discussed extensively but not conclusively, as the combination of factors varies among cultures and countries (e.g., Wilkinson et al., 2018; Liu et al., 2019; Orkusz et al., 2020). Dagevos (2021) reviewed the consumer acceptance in non-traditionally entomophagous societies, and his findings support this basic process. Unwillingness to try edible insects is part of food

[21] Grabowski, pers. communication, 2019.

[22] Sympathetic magic refers to assuming properties for one unknown object which were observed in another, similar object. If the individual has associated insects in general with filth, she or he is likely to associate filth with edible insects or the objects these insects touched. For details on this, see Rozin et al. (1986).

neophobia which by itself may affect many different foodstuffs. Food neophobia is another complex matter, and the degree of it varies according to different factors (reviewed e.g., in Dovey et al., 2008). Insects are particularly subjected to neophobia as not only they are no traditional foodstuffs, but also associated with the so-called 3 d's (dirt, diseases, and death). However, apart from unfamiliarity, attachment to meat seems another crucial factor. In contrast to insects, meat has been associated with the so-called 4 n's—natural, normal, necessary, and nice. The more devoted the consumers were to meat, the less interest in consuming insects were recorded. However, many studies presented insects as an alternative to meat (Dagevos, 2021), and this can be a fallacy since, on one hand, many insects do actually not taste like meat, and devoted meat consumers are prone to detect the differences. On the other hand, consumers highly attached to meat may feel morally driven into a corner (Schulte, 2019), fearing that any foodstuff termed as "meat alternative" may lead to personal pressure and, eventually, a decrease in supply. Indifference is another factor in not eating insects, because some consumers are not interested in the benefits of consuming insects as broadcasted *via* the media, such as sustainability and circularity.

The role of gender has been discussed controversially; on one hand, women are considered more careful in the choice of their foodstuffs because of their role as a mother, and ecologically beneficial foodstuffs should attract their interest. However, they are also cautious, and this is why in some studies, men in the traditional Western gender role consume more insects. This creates a situation in which largely accepted benefits of sustainability may be overruled by food safety concerns. On the other hand, more men than women are strongly attached to meat, and this would lead to less insect consumption. Dagevos (2021) however also points out that the kind of product (whole or processed etc.) also plays a role in gender-related insect consumption.

Food insect neophobia can be overcome by interest and expectations as created by information and experiences others shared with the individual (Grabowski, 2017). Information is important to grant a first contact with the issue that unexperienced consumer consider as low-risk. However, the personal experience of actually tasting insects should not take place long after the information (Dagevos, 2021). Upon eating, sensorial stimuli by the product, the processing, and the package create a new experience which can be evaluated *via* sensomics (Dunkel et al., 2014). Offering homogenized insects rather than whole animals is a low-threshold way to make this first step easier (Dagevos, 2021), as the animals' shape seems to be the triggering stimulus for insect-related disgust.

Apart from the deeply personal attitude of each consumer that may or may not lead to food insect neophobia, another aspect is the sum of general consumer perceptions and expectations from foodstuffs.

As mentioned before, food safety is one of those expectations, and first steps are undertaken to ensure it on a governmental base (see section Actual Processing, Transport, and Storage). This is deemed necessary as it provides a uniform way to assess quality and detect deviations. Food scandals have a particular impact on consumer acceptance, but the degree is modulated by the media rather than by scientific expertise, and still, the degree in which the scandals affect food choices in an individual varies (Mackenthun, 2006; Rieger et al., 2017). However, it may be expected that in novel foods with no high initial acceptance, a food scandal would have a large impact.

In many countries, some consumers tend to reduce consumption of animal-based foodstuffs (whatever the system is—intensive, extensive, or organic). The reasons to do so range from climate to animal welfare issues. However, there are always discrepancies between the articulated opinion of the consumers and their actual buying behavior which is also ruled by other factors. Still, the rejection of livestock mass rearing has not only lead to more ecological farming (short chain) but also to changes of food habits[23] in certain population sectors, e.g., vegetarian and vegan teenagers and young adults. Yet, although there are several initiatives to demonize livestock for meat production and meat consumption, modern livestock farms have brought huge benefits, and they are part of the solution for feeding the world population, along with increase of organic farming of ordinary livestock, insect farming, better and responsible use of resources, circular economy practices, and better technology and innovation applied on farm.[24]

As insect farming is done with large populations, it is in danger of getting as stigmatized as ordinary livestock farming. This goes along with animal welfare concerns which have existed for years, as the personal experience of one of the authors of this review has shown. In an ongoing survey regarding animal health and productive insects, the first results show a marked interest in establishing animal welfare concepts for farmed insects. On one side this requires acceptance of insects as sentient beings, but on the other side it was seen that the idea of insects being automatons that cannot feel distress or pain still lingers on, despite the fact that cognitive features have been documented in insects (e.g., Barron and Klein, 2016). Although it is not proven that all productive insects can experience distress and pain (resp. to which extend), it is being suggested that they should be farmed and killed using the precautionary principle, which means that the Brambell's five freedoms (**Table 6**) do apply to them and must be observed mandatorily, regardless of consumer expectations (Van Huis, 2020).

In this way, consumer acceptance is another complex field. Sustainability and safety are part of consumer acceptance. However, consumers react in a higher degree to flaws in sustainability and food safety than they will actually affect them (for examples, see **Table 7**). While food safety is not debatable as can be seen by the social impact food safety scandals have, sustainability may be crucial for purchase in some consumers, but a mere lip service in others. Still, consumer acceptance is the pivotal parameter if edible insects are to be placed on the market to a higher degree, and there are other decisive parameters such

[23]https://proveg.com/de/ernaehrung/anzahl-vegan-vegetarischer-menschen/, last accessed on April 23rd, 2021.
[24]https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cmef/farmers-and-farming/future-eu-livestock-how-contribute-sustainable-agricultural-sector_en and https://animaltaskforce.eu/About/About-us, last accessed on April 28th, 2021.

as food neophobia, meat attachment, consumer expectancies (including animal welfare) etc.

CONCLUSION AND OUTLOOK

The sustainability and safety of food insects are complex clockworks in which the outcome can be affected by even slight fine-tuning. The review showed that there are many turning points which can turn any production chain from sustainable to unsustainable and from safe to unsafe (**Table 7**). In this way, the initial question has to be answered with "jein." One important tool is to integrate traditional and non-traditional knowledge and skills for the benefit of all edible insect stakeholders (**Figure 3**). There is no need to re-invent the wheel in neither of the both movements.

For those that engage in traditional entomophagy, traditional knowledge on how to preserve this insect resource must be combined with scientific findings to cope with modern time's challenges, particularly those of food safety. Extensive systems like agroforestry parks are a viable way to manage wild non-migratory insects in the vicinity of villages (Tchibozo, 2015). If the demand for a given species still imperils the natural populations, steps to farm the species should be undertaken, turning traditional insect hunters and gatherers into mini-livestock farmers, rearing both local and new species (Nischalke et al., 2020).

For farmers thus, a thorough literature research looking for traditional and non-traditional knowledge is the first step before engaging economically in this sector. When farms are established (either as new enterprise or part of an existing agro-business), special attention should be laid on addressing sustainability issues, e.g., by choosing species that are already adapted to the climate (if energy costs are high), can be fed legally with feedstuffs (preferably side-streams) that are constantly available at low prices (or produced in the farm anyway), biosecurity (to avoid farmed insects to escape or wild animals to enter) and the insect production leftovers (so-called frass, i.e., insect feces and shed skins, feed residues, dead insects etc.) can be incorporated into the own agro-business or sold to third parties. Food safety can be achieved by the strict control of contaminants that could emanate from materials the animals are in contact with (housing, feed, tools etc.) and avoiding the entrance of wild insects that could enter the harvesting process.

Running the insect farm is accompanied by close monitoring and documentation, not only to evaluate the farm's yield but also to create data to be published in order to identify problems to be addressed in the future. Transparency in farming, killing, and processing the insects can create trust in consumers. For them, products must be designed and manufactured that have a true potential to be accepted by them. If the insects are to be processed and sold from the farm to the end consumer, special care must be laid on profiling possible consumer groups, e.g., with regard to age and gender, socio-economic background, life styles, consumer expectances and consumption habits that may go as far as developing products for sportive people, people supporting small local farms, flexitarians, people engaged in a low

TABLE 6 | Five freedoms in view of insect farming.

Freedom	Comment
Freedom from hunger or thirst	None
Freedom from discomfort	Providing an appropriate environment including shelter and a comfortable resting area must be achieved by balancing the species' needs and the possibilities to reflect them in a farming scenario, e.g., egg cartons in cricket rearing.
Freedom from pain, injury, or disease	First attempts for veterinary control of farms have been published (Eilenberg et al., 2015). They focus on observation and documentation, elimination of affected specimens and protection of the underlying breeding colony.
Freedom to express (most) normal behavior	For this, the ethology findings as recorded for each species should be the base.
Freedom from fear and distress	This may be the most difficult part to fulfill since it is not clear what the cognitive capacity of insects encompasses and, linked with this, to what extent they have to be observed.

TABLE 7 | Concrete examples of how the key parameters may affect sustainability and food safety of edible insects.

Key parameter	Effect on sustainability	Effect on food safety
Biology of the species	Farming termites with no biosecurity concept	Rearing carrion-feeding species
Level of knowledge of the foodstuff	Missing the opportunity to farm a species that complies with the requirements of an "ideal farm insect"	Not knowing the farmed species creates chronic food poisonings
Traditional knowledge	Losing information on how to make use of a certain local species	Failing to eliminate anti-nutrients and toxins *via* traditional preparation methods
Efficiency of traditional methods given the societal changes and needs	Overexploiting natural resources, leading to the extinction of the species	Storing raw insects in plastic bags without cooling, accelerating their putrifaction
Farming conditions	Having to pay high expenses for heating and water	Using contaminated feedstuffs or other materials that accumulate in the animals
Actual processing, transport, and storage	Having an accident while transporting large amounts of living palm weevils	Inappropriate heating treatments, lowering the quality and enabling the growth of pathogens
Consumer awareness and acceptance	Preferring insects that were not raised sustainably over those that actually were	Not instructing end consumers on how to prepare insects at home safely, leading to food-borne diseases

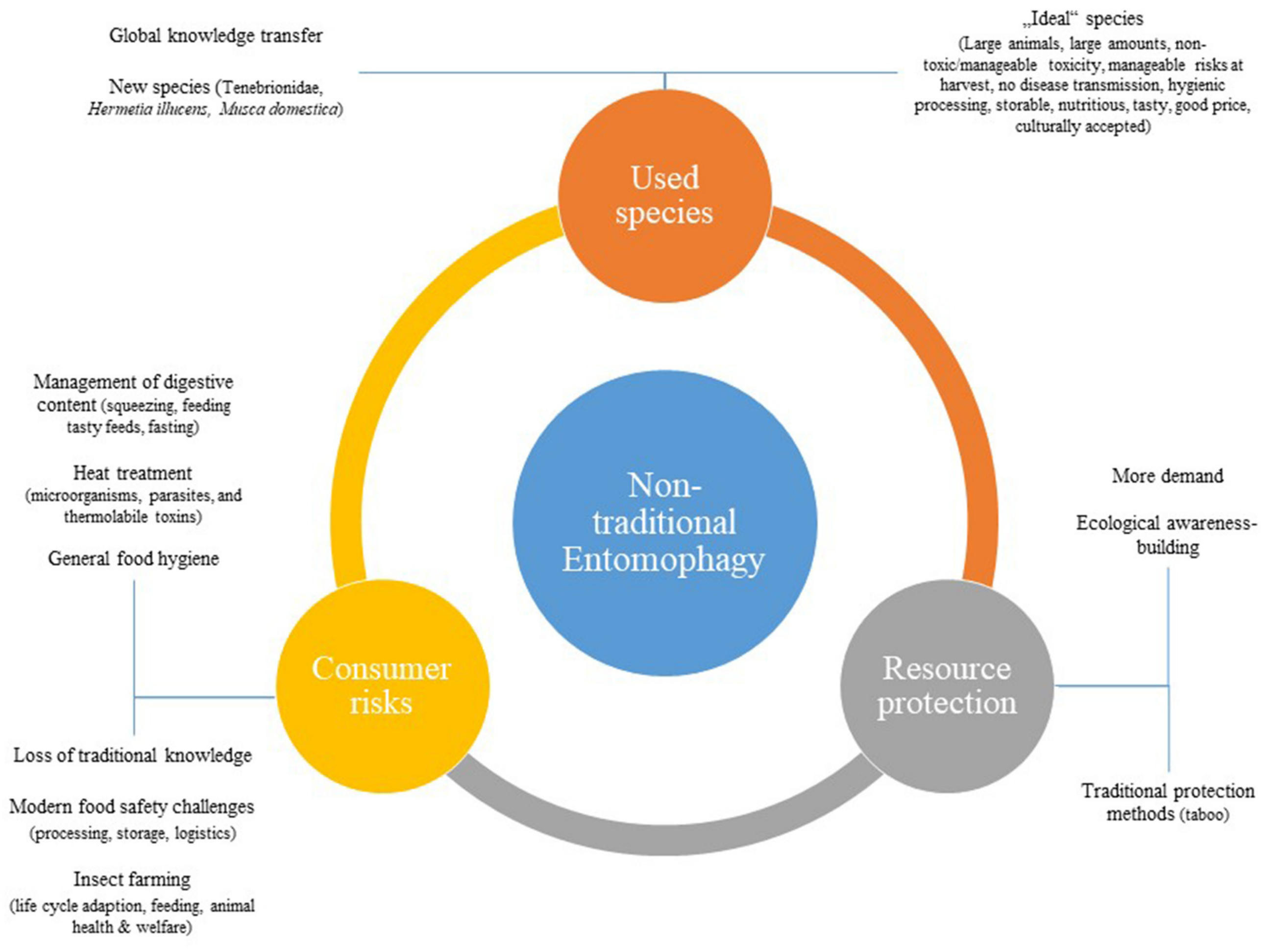

FIGURE 3 | Combination of traditional and non-traditional entomophagy.

carb or paleo diet etc. Above all, food safety must be guaranteed at any stage, basically comprising species-specific heat treatments and appropriate storage conditions, depending on the species and the product.

The industry willing to process insects will face similar challenges, but it may be expected that they can be coped with due to the high degree of technification. However, the microbiological status must be monitored very closely at all stages, including the post-production period until the best-before date.

Larger organizations like farmer associations, industry federations and other lobbying groups are predestined to develop consumer-tailored programs (including those for children) to promote consumption and inform about the benefits and risks of edible insects, i.e., nutritional, ecological, and cultural education of consumers and other stakeholders.

The public health sector has to establish a sound and practical legal framework along with corresponding monitoring systems (transferred, to a certain degree, to other entities like the larger organizations) to ensure the implementation of sustainability and food safety goals, just as already practiced in ordinary livestock.

The review has shown the complexity of this field and stressed the need to enhance research. There are many areas that require more science involvement along the entire production chain. Basic research should deal with filling the gaps in traditional entomophagy and detecting suitable farm insect species for the different climate zones so that energy costs at farming can be reduced. In primary production, life cycles and how to adapt them to farming conditions is one field, understanding farm insect physiology and pathology to ensure animal health as surveilled by veterinarians another, along with reaching appropriate nutrition and improving it when using agricultural side-streams. Herd managements concepts must be developed, and studies on ethology, stress and pain perception are necessary to cope with animal welfare issues. The latter is also important when insects are transported over longer distances, apart from the fact that inappropriate transport may endanger food safety and may mitigate the progress in sustainability obtained at earlier stages of the production chain. Processing technology is a vast area, and stresses to ensure food safety in combination with a maximum degree of sustainability will be necessary. Sustainable solutions to optimize energy spending should be preferred and implemented. Another focus should be non-food and non-feed uses of insect products including their by-products and side-streams (e.g., frass) to improve circularity. Regarding research with humans, special care must be set on evaluating risks for insect operators at all stages and consumers, e.g., allergies by handling or eating insects (Hamidou et al., 2017). Finally, understanding the acceptance or rejection of edible insects must be further examined, observing geography, consumer group, and insect product, so that tailored solutions can be found.

Therefore, a closer interaction between tradition and non-tradition would be desirable in the future. In order to be sustainable, local solutions must be implemented, i.e., traditional gathering when possible, farming when needed or desired. Farming must also be adapted to local conditions, from agroforestry over to small and medium farms to large plants that include all the steps from primary production to the final manufacture of a given foodstuff at industrial scale. Whenever synergies with other enterprises are possible, e.g., with green energy, agro-businesses, aquaculture or food processing, they should be established to increase circularity. However, it will be mandatory to ensure food safety in order to achieve a persisting consumer acceptance.

On a global level, edible insect farming has just started, bringing the species toward a long process of domestication. In contrast to the people that started keeping wild sheep or auerochs, modern insect farmers can start off a very different level of knowledge, but also must face many more challenges than their Neolithic colleagues.

AUTHOR CONTRIBUTIONS

The idea for the review by WS, FA, and MG, a concept developed and written by NG, enriched by local information by MF and FP (FVE), TP and AA (Germany), KB (Colombia), TC, PM, and SK (Cambodia), EC (Brazil), DG and JF (Mexico), RL and JM (Thailand), and ST (Benin), supervised by MP. All authors contributed to the article and approved the submitted version.

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