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Forage-Fed Insects as Food and Feed Source: Opportunities and Constraints of Edible Insects in the Tropics

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Farmed insects can provide an alternative protein source for humans, livestock, and fish, while supporting adaptation to climate change, generating income for smallholder farmers, and reducing the negative impacts of conventional food production, especially in the tropics. However, the quantity, nutritional quality and safety of insects greatly relies on their feed intake. Tropical forages (grasses and legumes) can provide a valuable and yet untapped source of feed for several farmed insect species. In this perspective paper, we provide a viewpoint of how tropical forages can support edible insect production. We also highlight the potential of tropical forage-based diets over those using organic agricultural or urban by-product substrates, due to their versatility, low cost, and lower risk of microbial and chemical hazards. The main bottlenecks relate to dependence on the small number of farmed insect species, and in public policy and market frameworks regarding the use of edible insects as food, feed and in industrial processes. This perspective will serve interested stakeholders in identifying urgent issues at the research, ethical, marketing and policy levels that can prevent the emergence of new, insect-based value chains and business models, and the nutritional, economic and environmental benefits they promise.

Keywords: edible insects, food security, sustainable development, business models, entomophagy policies

INTRODUCTION

Rapid population growth, climate change, and environmental degradation have put food security and nutrition at risk, especially in the global tropics. The need to feeding a growing population has resulted in the exploration of new food sources for humans, livestock, and fisheries. In recent years, insects have been proposed as an alternative food source for humans and livestock. Food derived from insects is considered more resource efficient (needing less land and water) than traditional livestock production systems (Payne et al., 2016). Several studies highlight the benefits of edible insects for human and animal health. Crickets (*Orthoptera*), flies (*Diptera*), and beetles (*Coleoptera*) do not differ significantly in their nutritional composition from traditional protein sources such as beef, chicken, and pork (van Huis et al., 2013; Payne et al., 2016; Frigerio et al., 2020; Stull, 2021). The use of insects as food for humans or feed for livestock is, however, not a new concept. Humans have used insects in their diets throughout history (van Huis et al., 2013).

More recently, insects have been seen as viable and sustainable protein sources for livestock (Chia et al., 2019). The increased relevance of insects as feed is reflected by a rapid increase in the number of patent applications related to insect food processing methods; a growing number of companies offering insects for human and animal consumption; and increased research on edible insects and greater social acceptance of such (Müller et al., 2016; Kim et al., 2019). The boom in interest in insects as food and feed is tracking attention across the globe as evidenced by the development of legislative frameworks for insect-based products (European Food Safety Authority, 2021); and projected increases in the global market volume from US$ 400 million to between US$700 million and US$1.2 billion by 2024 (Dunkel and Payne, 2016).

In this perspective article, we provide a viewpoint of how different tropical forage crops available from international gene banks and grown on farms can support the current insect farming industry, and how their incorporation in insect diets has potential for addressing food safety concerns while maintaining the high nutritional quality of insects for human and animal nutrition. The article is structured as follows: section Insect Farming as a Food Source in the Tropics provides an overview of insect farming as a feed and food source in the tropics; section Tropical Forages as a Feed Alternative for Farmed Insects focuses on feeding insects with tropical forages; section Examples of Successful Projects provides insights into some successful pilot projects; and section Toward Responsible Insect Farming in the Tropics sheds light on how to move toward responsible insect farming in the tropics. Section Concluding Remarks and Forward Look provides concluding remarks that help interested stakeholders in developing forage-based insect value chains in the tropics.

INSECT FARMING AS A FOOD SOURCE IN THE TROPICS

Leakey (2020) projects increasing food insecurity and environmental degradation in the tropics if the business-as-usual scenario continues. As a result, there is an urgent need for a paradigm shift where environmental sustainability, dietary diversity and productivity have equal value. Insect farming to produce food is a promising intervention. Compared to traditional livestock production systems, insect farming uses 50–90% less land per kg of protein produced and 40–80% less feed per kg of edible weight; produces 1.2–2.7 kg less greenhouse gas emissions per kg of live weight gain; and uses 1,000 L less water per kg of live weight gain (Payne et al., 2016). The tropics, where most insect species occur (Chapman, 2005), are very favorable for insect production since the edaphoclimatic conditions assure a steady production throughout the year under constant environmental conditions, and the natural occurrence of a broad variety of insect species eliminates the need to introduce non-native species that represent a risk of biological invasion (Jansson et al., 2019; Bang and Courchamp, 2020). Currently, most farmed insects at the industrial scale, however, belong to few species (Jansson et al., 2019), 12 in total, despite the existence of around 2,100 edible species (Jongema, 2017). This can exacerbate problems that exist in other food chains (e.g., crops, livestock) (Tisdell, 2001; Fanzo and Mattei, 2010; Bruford et al., 2015), such as diversity loss from overexploitation (Ramos-Elorduy, 2006; Malinga et al., 2020) and the risk of biological invasion in non-native regions, as well as create genetic erosion if no preventive measures are taken.

Insects also constitute a feasible alternative for animal feed, such as soybean and fishmeal, which is generally the largest expense in livestock production, representing 60–70% of the total production costs (Alqaisi et al., 2011; van Huis et al., 2013). As a result, small- and medium-scale farmers need alternatives that are both effective and affordable (Chia et al., 2019). Several cost factors are involved in insect farming, including facilities (i.e., laboratories and other infrastructure and resources), labor requirements (e.g., natural oviposition vs. artificial larvae infestation in the substrate), lifecycles and diets of insects (Chia et al., 2019).

TROPICAL FORAGES AS A FEED ALTERNATIVE FOR FARMED INSECTS

For insects to be considered viable as a food for humans or livestock, they must be provided with an adequate diet. Most often, small-scale farmed insects are herbivores that rely on crop residues (Chia et al., 2018; Jansson et al., 2019). Larger-scale insect farming is sometimes based on feeds that are in direct competition with human diets (e.g., maize, soybean, oats, wheat; see **Table 1**), and may contain ingredients with associated environmental impacts (Miglietta et al., 2015). For instance, some commercial diets for crickets include grains and fish meal to supply protein requirements, decreasing the sustainability of the entire chain (Lundy and Parrella, 2015; Bawa et al., 2020). Based on that, we propose that tropical forages can be used as an additional feed source in insect production.

TABLE 1 | Commonly farmed insects for food and feed.

Common name	Species
Industry-scale farmed insects for food and feed[a]	
Crickets	*Acheta domesticus*
	Gryllodes sigillatus
	Gryllus bimaculatus
Mealworms	*Tenebrio molitor*
	Zophobas morio
	Alphitobius diaperinus
Black soldier flies	*Hermetia illucens*
House flies	*Musca domestica*
Wax moths	*Galleria mellonella*
Locusts	*Locusta migratoria*
Sun beetles	*Pachnoda marginata peregrina*
Cockroaches	*Blaptica dubia*

Source: own elaboration based on [a]Jansson et al. (2019).

Tropical forages refer to planted grasses and legumes that are used to feed livestock in the tropics and include species such as *Megathyrsus maximus* (syn. *Panicum maximum*), *Urochloa* spp. (syn. *Brachiaria* spp.) or *Arachis pintoi* (see **Table 1**). Most often, tropical forages are used in places where other crops cannot be produced (e.g., on low-fertility and marginal soils). Among the common features of this group of plants are their relatively high biomass production and adaptation to continuous clipping, browsing, or grazing from animals, followed by vegetative re-growth (Capstaff and Miller, 2018). Tropical forages can supply enough biomass and serve as a steady supply of vegetative material to feed herbivore and omnivorous insects over one to several seasons. Tropical forages can also be conserved when there is a production surplus, e.g., as hay or silage with potential for insect feeding.

It is possible to enhance the nutritional content of insects by using tropical forages (Oonincx et al., 2020). Recent studies report that the protein content of crickets increases according to the protein supplementation of feed. Feeding for example dry pumpkin pulp or enriched flaxseed oil increases the vitamin B and omega 3 and 6 contents, respectively (Bawa et al., 2020; Oonincx et al., 2020). Tropical forages have better nutritional values than e.g., crop residues, and herbivore insects prefer most often soft (e.g., green leaves from forage crops) over hard plant material (e.g., stubble from crop residues) (Caldwell et al., 2016). Additionally, insects fed with tropical forages would not compete with food production for human consumption as is the case with grain-based insect feeds. In Uganda, the edible cricket *Ruspolia differens* (Orthoptera: Tettigoniidae) was found feeding on 19 grasses, including *Megathyrsus maximus, Urochloa ruziziensis, Chloris gayana, Cynodon dactylon, Setaria sphacelate,* and *Pennisetum purpureum*, preferring inflorescences or seeds over stems or leaves and showing a variability in host plant preference through the different life stages (Opoke et al., 2019). Also, diets based on grass inflorescences from different species influence maximal weight, survival, shorter development time and content of fatty acids of *R. differens,* being *U. ruziziensis, P. purpureum, S. sphacelata*, and *C. gayana* efficient for rearing insects for food and feed in sub-Saharan Africa (Rutaro et al., 2018; Malinga et al., 2020).

However, there is significant uncertainty about what constitutes optimal diets for farmed insects. Insects can compensate for the detrimental effects of an unbalanced diet through different physiological and behavioral mechanisms. Adequate food ingestion with the proper protein and carbohydrate ratios, however, results in better insect performance (Barragán-Fonseca, 2018). The nutritional requirements vary for each insect species and diets determine their nutritional content. For omnivorous farmed insects, these are complex and difficult to determine because of the broad variety of feed sources and substrates, but this characteristic also allows for more versatile diets to ensure their growth and development (Cortes Ortiz et al., 2016; Barragán-Fonseca et al., 2017; Hanboonsong and Durst, 2020).

There exists a large diversity of tropical forages, with great variation in terms of forage yield, agricultural suitability, nutrient content, and production constraints (Martens et al., 2012; Lee, 2018). An important collection of tropical forage diversity is safeguarded in the CGIAR gene banks of the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT) and the International Livestock Research Institute (ILRI), with over 22,000 accessions of tropical forage grasses and legumes from over 75 countries (The Alliance of Bioversity International CIAT, 2021). This diversity is a forage resource yet to be explored and used in insect farming. **Table 1** provides an overview of commonly farmed insects and **Table 2** on the forages that could potentially be used as diet, based on the comparison of the nutritional contents of commonly used diets and tropical forages. For crickets, *Andropogon* spp. could potentially replace whole yellow corn flour, mealworms could be fed with *Megathyrsus maximus* instead of white wheat, and sun beetle diets could be changed from brewer's yeast to *Arachis pintoi*, among others. Creative approaches are needed to identify the best-suited forages and to mix them in adequate ratios to supply insects with the required nutrients, increasing their productivity, and thereby, contributing to the sustainable intensification of animal-source food production systems.

Tropical forages available in the international gene banks, but also on farms, have the potential to become a part of the diets of farmed herbivorous insects. Forage-based insect diets would also contribute to the transition to circular economies for the agricultural sector. Insects produced with such diets can be used for both human consumption and as feed for poultry, swine, or fish. This would lead to numerous benefits and opportunities, such as the creation of new industries, small-scale businesses and jobs, income diversification, more balanced human diets, the protection of endangered species and ecosystems (e.g., marine ecosystems or forests), the reduction of greenhouse gas emissions, increases in above- and below-ground biodiversity and the protection of water resources, and thus contribute to achieving some of the Sustainable Development Goals (UN, 2021), i.e., those related to ending poverty, zero hunger, climate action, clean water and sanitation, decent work and economic growth, industry innovation and infrastructure, responsible consumption and production, life below water and life on land (Chia et al., 2019).

EXAMPLES OF SUCCESSFUL PROJECTS

Two projects in Kenya and Colombia show the impact of insect production as feed in small and medium-sized farms. In Kenya, the International Centre for Insect Physiology and Ecology (ICIPE) and Wageningen University trained more than 1,000 farmers on the production of black soldier fly larvae in organic waste substrates for feeding their animals and selling larvae to feed mills, resulting in 37 new insect-based enterprises and the establishment of cost-effective modular insect production systems (Dicke, 2019; Barragán-Fonseca et al., 2020). In Colombia, the National University of Colombia implemented different projects related to insect production for replacing 15% of traditional fish feed by black soldier fly larvae, with ex-combatants of the FARC-EP guerrilla in the Tolima

TABLE 2 | Content of common diets use in large-scale insect industry and potential forage species as alternatives for insect feed.

Common diets - nutritional content[a]			Potential forages as alternatives for insect feed[c]		
Source	**Protein**	**Crude fiber**	**Protein[c]**	**Crude fiber[b]**	**Species**
Whole yellow corn flour	6.9	7.3	8.3	31.6	*Andropogon* spp.
Carrot, dehydrated	8.1	23.6	9.7	36.1	*Pennisetum purpureum*
Dry potato flour	8.3	6.6	9.8	31.3	*Cynodon dactylon (cultivars and hybrids)*
White wheat	11.3	12.2	11.2	37.3	*Megathyrsus maximus*
Crude wheat bran	15.5	42.8	14	34.2	*Stylosanthes* spp.
Alfalfa pellets	16	27	14.2	31.5	*Paspalum notatum*
Dry egg yolk	32.2	0	14.6	29.9	*Urochloa* spp. (cultivars and hybrids)
Whole soy flour	34.5	9.6	18.9	30.7	*Centrosema molle*
Dry milk, skim	36.2	0	20.6	26.1	*Cratylia argentea*
Baker's yeast	38.3	21	20.6	26.1	*Desmodium heterophyllum*
Brewer's yeast	53.3	20	21.4	27.3	*Arachis pintoi*
Dry beef liver	68	0	23.3	19.9	*Leucaena leucocephala*
			9.0	36.9	*Chloris gayana*
			7.7	38	*Setaria sphacelata*

Source: own elaboration based on [a]Cortes Ortiz et al. (2016); [b]Of fresh aerial part; INRAE et al. (2020); [c]Rao et al. (2015); Schultze-Kraft et al. (2018).

Department, also addressing SDG 16 on peace, justice and strong institutions (Barragán-Fonseca et al., 2020). Currently there are research initiatives led by the International Centre of Insect Physiology and Ecology (ICIPE), academic institutions (e.g., University of Copenhagen, Wageningen University) and governmental institutions (e.g., The Netherlands Organization for Scientific Research), such as GREEiNSECT and ILIPA, which aim at producing scientific evidence for insect production in small-, medium- and large-scale industries and developing the commercial potential for food and feed, contributing enormously to the growth of this sector in the tropics.

Apart from their use as food and livestock feed, insects can also be sold (alive or processed) on other niche markets with price premiums, such as to zoos or pet owners, generating additional income for producers. Processing methods range from more artisanal (e.g., sun and oven drying, smoking, curing, grounding) to more refined industrial techniques (Melgar-Lalanne et al., 2019). New products are being developed constantly to satisfy the increasing demands of different niche markets. For human diets, a broad range of insect-based ingredients and products are already available on the market, which include cricket powder and food coloring or oils, as well as dishes in restaurants and snacks. For instance, in Thailand, where most of the sector is on a small-scale in rural areas, new market opportunities in gourmet restaurants and gastronomy tourism allowed the development of edible crickets and silkworm products and their industrialization in the main cities of the country (Halloran et al., 2016). Forage-based insect diets help to reduce the microbiological and chemical hazard (i.e., microorganisms, viruses, prions, pesticide residues) associated with substrates like animal or agriculture by-products or kitchen waste (EFSA Scientific Committee, 2015; Dobermann et al., 2017; Gałecki and Sokół, 2019), resulting in higher food safety of the derived products for both human and animal consumption.

TOWARD RESPONSIBLE INSECT FARMING IN THE TROPICS

The European Union (EU) followed by the United States and Canada leads the global edible insect market and industry (Bermúdez-Serrano, 2020). Consequently, the most complete and strict legislation related to the use of edible insects is found in the EU, where the insects (whole or parts of) are considered a novelty food that can be marketed throughout the region. Policies that regulate the type and quality of insect feed, insect commercialization, and more recently, the safety of specific species for human consumption are decreed by the European Food Safety Authority (EFSA), EU member countries, and Switzerland (Der Schweizerische Bundesrat, 2021). In January 2021, dried larvae of the species *Tenebrio molitor* (mealworms) were declared safe for human consumption by the EFSA, highlighting that the levels of contaminants will depend on those present in the substrates used as insect feed. A review by Lähteenmäki-Uutela et al. (2017) showed that, despite the increasing number of companies involved in the development of insect-based products and the growing insect market, the United States, Canada, China and Mexico lack regulations regarding the safety of insect food and feed products. Australia and New Zealand have regulations in the Food Standard Code for the species *Zophobas morio*, *Acheta domesticus*, and *Tenebrio molitor*, without clear definitions regarding food and feed safety (Lähteenmäki-Uutela et al., 2021). A high quantity of biological, chemical and allergenic risks are associated with this industry, as with any other kind of food (EFSA Scientific Committee, 2015), highlighting the urgent need for research on this matter. In addition, the participation of non-governmental institutions like the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) is necessary to guarantee the safety of insect products and to establish an international market, yet no such standards are included in the Codex Alimentarius Commission (Lähteenmäki-Uutela et al., 2021).

In tropical countries in Asia and America, legislative frameworks for insect production, commercialization and consumption are either insufficient or non-existent. In several countries, insects are not even considered food, undermining their potential role in the diets of humans and animals (Bermúdez-Serrano, 2020). In Thailand, the use of edible insects is an ancestral practice and although there are no food safety policies, licenses are needed to establish large-scale cricket farms, which are issued by the Food and Drug Administration of Thailand. Also, governmental institutions have released guidelines for cricket farming (Halloran et al., 2015, 2017; FAO, 2021). The situation is similar in Mexico, where insect production is regulated by the organic products law, which focuses on the promotion, conservation and avoidance of overexploitation of only four species: *Aegiale hesperiaris*, *Liometopum apiculatum*, *Cerambycidae* larvae and ant eggs (Lähteenmäki-Uutela et al., 2021). Other Latin American countries, such as Colombia, Brazil, or Argentina, do not have explicit regulations in this regard and tend to follow the Codex Alimentarius Commission standards. In contrast, there is legislation in place regarding edible insects in most tropical African countries (Grabowski et al., 2020). Kenya and Uganda are the two counties currently leading the setting up of standards for the use of insects as food and feed on the African continent (Egonyu et al., 2021). However, such standards still need to fully facilitate the potential of edible insects as an industrial endeavor (Musundire et al., 2021).

CONCLUDING REMARKS AND FORWARD LOOK

Insects are a viable option for supplying the growing demand for protein in the tropics, especially given the need to adapt to and mitigate climate change, potentially contributing to the UN's 2030 agenda. The advantages of insect farming in the tropics include a greater biodiversity, production throughout the year under stable environmental conditions and the contribution to at least 8 Sustainable Development Goals. This has led to the development of an emerging industry through initiatives based on black soldier fly production for fisheries in Kenya and Colombia. Organic residues and substrates, commonly used for this purpose, may, however, represent a hazard for both fishery and human health. We propose a new approach for insect-based value chains by integrating tropical forage-based diets in edible insect production systems, given the yet untapped forage diversity in international gene banks and on farms. Compared to commercial diets, tropical forages are a low-cost feed source for insects, with high dietary versatility, that provide opportunities for the transition to sustainable, circular economies. We found the main bottlenecks in the lack of specific regulations, the dependence on few species for large-scale industrial insect production and consumer food safety.

Further studies should focus on assessing several species of tropical forages to be included in the diets of commonly farmed insects Also, studies comparing the ease of using tropical forages as insect feed against that of conventional feed (commercial diets or organic waste) need to be performed. There also exists a need to further harmonize rearing, mass production, genetic diversity and harvesting of insects with consumption practices and strengthening of value chains and legislations. Knowledge from communities traditionally using insects as feed and food need to be considered since they can provide valuable insights. The synergies of these approaches will help the development of alternatives to feed both humans and livestock in a nutritious, secure and sustainable way.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PE, LH, SB, and JC: conceptualization, methodology, and resources. PE and LH: formal analysis. PE, LH, SB, NP, and JC: writing the original draft and review and editing. SB and JC: supervision, funding acquisition, and project administration. All authors contributed to the article and approved the submitted version.

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REFERENCES

Alliance of Bioversity International and CIAT (2021). *Tropical Forage Diversity*. Cali, Colombia: The Alliance of Bioversity International and CIAT. Available online at: https://ciat.cgiar.org/what-we-do/crop-conservation-and-use/tropical-forage-diversity/ (accessed May 21, 2021).

Alqaisi, O., Asaah, O., and Hemme, T. (2011). Global view on feed cost and feed efficiency on dairy farms. *All About Feed* 2, 1–5. Available online at: https://www.allaboutfeed.net/animal-feed/feed-processing/global-view-on-feed-cost-and-feed-efficiency-on-dairy-farms/ (accessed October 27, 2021).

Bang, A., and Courchamp, F. (2020). Industrial rearing of edible insects could be a major source of new biological invasions. *Ecol. Lett.* 24, 393–397. doi: 10.1111/ele.13646

Barragán-Fonseca, K. (2018). *Flies Are What They Eat - Tailoring Nutrition of BSF (Hermetia illucens) for Larval Biomass Production and Fitness.* (dissertation)]. Wageningen, Netherlands: Wageningen University.

Barragán-Fonseca, K., Cortés Urquijo, J., Dicke, M., and Quintana, A. P. (2020). "South-south inspiration to connect SDG2 and SDG16 in former conflict areas: promoting sustainable livelihoods of ex-insurgents in Colombia by insect farming," in *Wageningen Livestock Research, Public Report*, 1289.

Barragán-Fonseca, K. B., Dicke, M., and van Loon, J. J. A. (2017). Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed - a review. *J. Insects Food Feed* 3, 105–120. doi: 10.3920/JIFF2016.0055

Bawa, M., Songsermpong, S., Kaewtapee, C., and Chanput, W. (2020). Effect of diet on the growth performance, feed conversion, and nutrient content of the house cricket. *J. Insect Sci*. 20, 1–10. doi: 10.1093/jisesa/ieaa014

Bermúdez-Serrano, I. M. (2020). Challenges and opportunities for the development of an edible insect food industry in Latin America. *J. Insects Food Feed* 6, 537–556. doi: 10.3920/JIFF2020.0009

Bruford, M. W., Ginja, C., Hoffmann, I., Joost, S., Wengel, P. O., Alberto, F. J., et al. (2015). Prospects and challenges for the conservation of farm animal genomic resources, 2015-2025. *Front. Genet*. 6:314. doi: 10.3389/fgene.2015.00333

Caldwell, E., Read, J., and Sanson, G. D. (2016). Which leaf mechanical traits correlate with insect herbivory among feeding guilds? *Ann. Bot*. 117, 349–361. doi: 10.1093/aob/mcv178

Capstaff, N. M., and Miller, A. J. (2018). Improving the yield and nutritional quality of forage crops. *Front. Plant Sci*. 9:535. doi: 10.3389/fpls.2018.00535

Chapman, A. (2005). *Numbers of Living Species in Australia and the World*. Canberra, Australia: Department of Environment and Heritage, Australian Government.

Chia, S. Y., Tanga, C. M., Osuga, I. M., Mohamed, S. A., Khamis, F. M., Salifu, D., et al. (2018). Effects of waste stream combinations from brewing industry on performance of black soldier fly, Hermetia illucens (Diptera: Stratiomyidae). *PeerJ* 6:e5885. doi: 10.7717/peerj.5885

Chia, S. Y., Tanga, C. M., van Loon, J. J., and Dicke, M. (2019). Insects for sustainable animal feed: inclusive business models involving smallholder farmers. *Curr. Opin. Environ. Sustain*. 41, 23–30. doi: 10.1016/j.cosust.2019.09.003

Cortes Ortiz, J., Ruiz, A., Morales-Ramos, J., Thomas, M., Rojas, M., Tomberlin, J., et al. (2016). "Insect mass production technologies," in *Insects as Sustainable Food Ingredients: Production, Processing and Food Applications*, eds. A. T. Dossey, J. A. Morales-Ramos, and M. G. Rojas (London: Academic Press), 153–201.

Der Schweizerische Bundesrat (2021). *Verordnung über tierische Nebenprodukte (VTNP) vom 25. Mai 2011 (Stand am 1. Mai 2021) Fassung gemäss Ziff. I der V vom 25. April 2018, in Kraft seit 1. Juni 2018 (AS 2018 2097)*. Bern, Switzerland: Der Schweizerische Bundesrat. Available online at: https://www.fedlex.admin.ch/eli/cc/2011/372/de (accessed October 27, 2021).

Dicke, M. (2019). "Improving livelihood by increasing livestock production in Africa: An agribusiness model to commercially produce high quality insect-based protein ingredients for chicken, fish and pig industries," in *Food and Business Global Challenges Programme. Final Report*. Netherlands Organisation for Scientific Research – NWO.

Dobermann, D., Swift, J. A., and Field, L. M. (2017). Opportunities and hurdles of edible insects for food and feed. *Nutr. Bull*. 42, 293–308. doi: 10.1111/nbu.12291

Dunkel, F. V., and Payne, C. (2016). "Introduction to edible insects" in *Insects as Sustainable Food Ingredients: Production, Processing and Food Applications*, eds. A. T. Dossey, J. A. Morales-Ramos, and M. G. Rojas (London: Academic Press), 1–27.

EFSA Scientific Committee (2015). Scientific Opinion on a risk profile related to production and consumption of insects as food and feed. *EFSA J*. 13:60. doi: 10.2903/j.efsa.2015.4257

Egonyu, J. P., Kinyuru, J., Fombong, F., Ng'ang'a, J., Abdullahi Ahmed, Y., and Niassy, S. (2021). Advances in insects for food and feed. *Int. J. Trop Insect. Sci.* 41, 1903–1911. doi: 10.1007/s42690-021-00610-8

European Food Safety Authority (2021). *Edible Insects: The Science of Novel Food Evaluations*. Available online at: https://www.efsa.europa.eu/en/news/edible-insects-science-novel-food-evaluations (accessed May 10, 2021).

Fanzo, J., and Mattei, F. (2010). "Ensuring agriculture, biodiversity and nutrition remains central to addressing the MDG1 hunger target," in *Biodiversity and Sustainable Diets United Against Hunger*, eds. B. Burlingame and S. Dernini (Rome: FAO), 44–54.

FAO (2021). *Looking at Edible Insects From a Food Safety Perspective. Challenges and Opportunities for the Sector*. Rome: FAO.

Frigerio, J., Agostinetto, G., Sandionigi, A., Mezzasalma, V., Berterame, N. M., Casiraghi, M., et al. (2020). The hidden 'plant side' of insect novel foods: a DNA-based assessment. *Food Res. Int*. 128:108751. doi: 10.1016/j.foodres.2019.108751

Gałecki, R., and Sokół, R. (2019). A parasitological evaluation of edible insects and their role in the transmission of parasitic diseases to humans and animals. *PLoS ONE* 14:e0219303. doi: 10.1371/journal.pone.0219303

Grabowski, N. T., Tchibozo, S., Abdulmawjood, A., Acheuk, F., M'Saad Guerfali, M., Sayed, W. A., et al. (2020). Edible insects in Africa in terms of food, wildlife resource, and pest management legislation. *Foods* 9:502. doi: 10.3390/foods9040502

Halloran, A., Hanboonsong, Y., Roos, N., and Bruun, S. (2017). Life cycle assessment of cricket farming in north-eastern Thailand. *J. Clean. Prod*. 156, 83–94. doi: 10.1016/j.jclepro.2017.04.017

Halloran, A., Roos, N., Eilenberg, J., Cerutti, A., and Bruun, S. (2016). Life cycle assessment of edible insects for food protein: a review. *Agron. Sustain. Dev.* 36:57. doi: 10.1007/s13593-016-0392-8

Halloran, A., Vantomme, P., Hanboonsong, Y., and Ekesi, S. (2015). Regulating edible insects: the challenge of addressing food security, nature conservation, and the erosion of traditional food culture. *Food Secur*. 7, 739–746. doi: 10.1007/s12571-015-0463-8

Hanboonsong, A., and Durst, P. (2020). *Guidance on Sustainable Cricket Farming - A Practical Manual*. Bangkok: FAO

INRAE, CIRAD, AFZ, and FAO (2020). *Feedipedia - Animal Feed Resources Information System. List of Feeds*. Available online at: https://www.feedipedia.org/content/feeds?category=13593 (accessed October 27, 2021).

Jansson, A., Hunter, D., and Berggren, Å. (2019). *Insects as Food – An Option for Sustainable Food Production?* Uppsala, Sweden: Swedish University of Agricultural Sciences.

Jongema, Y. (2017). *List of Edible Insects of the World, 2017*. Available online at: https://www.wur.nl/en/Research-Results/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm (accessed April 29, 2020).

Kim, T. K., Yong, H. I., Kim, Y. B., Kim, H. W., and Choi, Y. S. (2019). Edible insects as a protein source: a review of public perception, processing technology, and research trends. *Food Sci. Anim. Resour*. 39, 521–540. doi: 10.5851/kosfa.2019.e53

Lähteenmäki-Uutela, A., Grmelová, N., Hénault-Ethier, L., Deschamps, M. H., Vandenberg, G. W., Zhao, A., et al. (2017). Insects as food and feed: laws of the European union, United States, Canada, Mexico, Australia, and China. *Eur. Food Feed Law Rev*. 12, 22–36. Available online at: https://effl.lexxion.eu/article/EFFL/2017/1/6 (accessed October 27, 2021).

Lähteenmäki-Uutela, A., Marimuthu, S., and Meijer, N. (2021). Regulations on insects as food and feed: a global comparison. *J. Insects as Food Feed* 7, 1–8. doi: 10.3920/JIFF2020.0066

Leakey, R. R. B. (2020). A re-boot of tropical agriculture benefits food production, rural economies, health, social justice and the environment. *Nat. Food* 1, 260–265. doi: 10.1038/s43016-020-0076-z

Lee, M. A. (2018). A global comparison of the nutritive values of forage plants grown in contrasting environments. *J. Plant Res*. 131, 641–654. doi: 10.1007/s10265-018-1024-y

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* 10:118785. doi: 10.1371/journal.pone.0118785

Malinga, G. M., Valtonen, A., Hiltunen, M., Lehtovaara, V. J., Nyeko, P., and Roininen, H. (2020). Performance of the African edible bush-cricket, Ruspolia differens, on single and mixed diets containing inflorescences of their host plant species. *Entomol. Exp. Appl*. 168, 448–459. doi: 10.1111/eea.12932

Martens, S. D., Tiemann, T. T., Bindelle, J., Peters, M., and Lascano, C. E. (2012). Alternative plant protein sources for pigs and chickens in the tropics - Nutritional value and constraints: a review. *J. Agric. Rural Dev. Trop. Subtrop*. 113, 101–123. Available online at: http://nbn-resolving.de/urn:nbn:de:hebis:34-2012092441794 (accessed October 27, 2021).

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, 1166–1191. doi: 10.1111/1541-4337.12463

Miglietta, P. P., De Leo, F., Ruberti, M., and Massari, S. (2015). Mealworms for food: a water footprint perspective. *Water* 7, 6190–6203. doi: 10.3390/w7116190

Müller, A., Evans, J., Payne, C. L. R., and Roberts, R. (2016). Entomophagy and power. *J. Insects Food Feed* 2, 121–136. doi: 10.3920/JIFF2016.0010

Musundire, R., Ngonyama, D., Chemura, A., Ngadze, R. T., Jackson, J., Matanda, M. J., Tarakini, T., Langton, M., and Chiwona-Karltun, L. (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

Oonincx, D. G. A. B., Laurent, S., Veenenbos, M. E., and van Loon, J. J. A. (2020). Dietary enrichment of edible insects with omega 3 fatty acids. *Insect Sci*. 27, 500–509. doi: 10.1111/1744-7917.12669

Opoke, R., Nyeko, P., Malinga, G. M., Rutaro, K., Roininen, H., and Valtonen, A. (2019). Host plants of the non-swarming edible bush cricket *Ruspolia differens*. *Ecol. Evol*. 9, 3899–3908. doi: 10.1002/ece3.5016

Payne, C. L. R., Scarborough, P., Rayner, M., and Nonaka, K. (2016). Are edible insects more or less "healthy" than commonly consumed meats? A comparison using two nutrient profiling models developed to combat over- and undernutrition. *Eur. J. Clin. Nutr*. 70, 285–291. doi: 10.1038/ejcn.2015.149

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

Rao, I., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., et al. (2015). LivestockPlus - the sustainable intensification of forage-based agricultural systems to improve livelihoods and ecosystem services in the tropics. *Trop. Grasslands Forrajes Trop*. 3, 59–82. doi: 10.17138/TGFT(3)59-82

Rutaro, K., Malinga, G. M., Lehtovaara, V. J., Opoke, R., Nyeko, P., Roininen, H., et al. (2018). Fatty acid content and composition in edible Ruspolia differens feeding on mixtures of natural food plants. *BMC Res. Notes* 11:687. doi: 10.1186/s13104-018-3792-9

Schultze-Kraft, R., Rao, I. M., Peters, M., Clements, R. J., Bai, C., and Liu, G. (2018). Tropical forage legumes for environmental benefits: an overview. *Trop. Grasslands Forrajes Trop*. 6, 1–14. doi: 10.17138/TGFT(6)1-14

Stull, V. J. (2021). Impacts of insect consumption on human health. *J. Insects Food Feed* 7, 1–20. doi: 10.3920/JIFF2020.0115

Tisdell, C. (2001). Socioeconomic causes of loss of animal genetic diversity: analysis and assessment. *Ecol. Econ*. 45, 365–376. doi: 10.1016/S0921-8009(03)00091-0

UN (2021). *The 17 Goals. United Nations – Department of Economic and Social Affairs, Sustainable Development*. New York City, NY. Available online at: https://sdgs.un.org/goals (accessed October 27, 2021).

van Huis, A., van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., et al. (2013). *Edible Insects. Future Prospects for Food and Feed Security*. Rome, Italy: Food and Agriculture Organization of the United Nations.

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