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**

Leaky (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** | |
| 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 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 regrowth (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 spicatata,* 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. spicatata,* 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...
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; Galecki and Sokól, 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 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 Tenebrio molitor,  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 countries 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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Espitia Buitrago et al. Forage-Fed Insects as Food-Feed Source

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