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EDITORIAL

Advances in insects for food and feed

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Abstract
This Special Issue presents the outcomes from the 23rd African Association of Insect Scientists' Conference held in Cote D'Ivoire, in connection with similar initiatives within and outside Africa. Over 65 scientific papers from several countries, worldwide, were submitted, of which about 40 were accepted and published. The issue focused on new advances in the value chain of edible insects in Africa and beyond. An innovative light-emitting diode technology for mass harvesting of edible grasshopper has been developed. The nutrient composition of insects such as the desert locust has been evaluated. Organic waste streams have been found to affect insect productivity and nutritional value. Insect-based feed increases the nutritional quality of poultry meat. Conventional processing methods reduce microbiological hazards in edible insects. Bioaccumulation of heavy metals, excessive microbial loads and pesticides residues threaten safety of some edible insects, if quality control measures are not developed. Climate change will impede availability of edible insects; hence, necessitating upscaling of mass production technologies and sound conservation practices. Safety and hygiene, on the other hand, hamper the acceptability of insects as food and/or feed, particularly in developed countries. Food fortification with insects and isolation of bioactive compounds from them are new highlights in the Special Issue, which were previously under-explored in Africa. The application of modern food processing technology in the development of new products and the medicinal or commercial value derivable from edible insects and their therapeutic functions are excellent opportunities for expanding the sector. Since disgust factors exist, mass sensitisation on the benefits of consuming insects and insect-based products is a must. We believe that the new frontiers on insects for food, feed and other uses that have been presented in this special issue will undoubtedly stimulate more debates and collaborations in the sector within Africa and beyond.

Keywords Biology · Mass-production · Nutrition · Processing · Socioeconomics and policy

Introduction

The past decade has seen people embracing insect consumption like never before. The first international conference on insects for food and feed, organised by the Wageningen University and Research and the Food and Agricultural Organization of the United Nations (FAO), held in Wageningen, the Netherlands, in May 2014, brought together over 450 participants from 45 countries. Since then, several other initiatives have been held with similar agendas. Insects comprise the most diverse and numerous groups in the animal kingdom and have colonised nearly all biotope types. Their role in the ecological food chain is indisputable, and they have served as food for humans and animals for millennia, as shown by fossils of placental mammals from the post-Cretaceous period (Emerling et al. 2018).

Recent research reports demonstrate that edible insects have comparable levels of protein, fat, energy, essential amino acids, flavonoids, minerals, and vitamins to most conventional food and feed sources, and sometimes have even richer levels (van Huis et al. 2013; Kelemu et al. 2015; Dobermann et al. 2017). The potential for using insects as 'mini livestock' is high. Owing to their high feed-conversion efficiency, producing insects requires less water and land,

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and they emit fewer greenhouse gasses and ammonia than conventional livestock does (Oonincx et al. 2010; Oonincx and De Boer 2012). Furthermore, insects are a rich source of chitin–the second-most abundant natural biopolymer after cellulose. In recent years, chitin has been used to substitute synthetic compounds in several feeds, food, and pharmaceutical products (Shahidi et al. 1999).

Edible insects, therefore, can fill nutritional gaps and improve human health, such as iron deficiency among children below five years old and women of reproductive ages. In addition, insects are excellent alternative replacements for the expensive conventional fishmeal or plant-based protein additives used in livestock and fish feeds, which account for more than 60% of production costs (Ssepuuya et al. 2017; Onsongo et al. 2018). Edible insects are also viewed as vehicles through which income can be generated, peace attained, and the general well-being of humans improved.

Despite their importance in the past, insects are yet in recent times to be accepted fully as human food or animal feed in many parts of the world. As insects have never been officially accepted as food or feed items, the regulatory framework was not conducive for the exploitation of insects for food or feed. However, with the rising demand for food, especially protein sources, attributable to the increasing human population, which is projected to reach 10 billion by 2050 (FAO 2017), there has recently been a shift of interest towards exploring alternative protein sources. Furthermore, arable land is dwindling owing to anthropogenic activities and climate change. As a result, meeting future food demands requires innovative, environmentally friendly and sustainable approaches to be taken, for which the edible insect sector fits in well. About 2000 insect species are consumed globally (Jongema 2017), with over 500 of these consumed by more than 300 million Africans (van Huis et al. 2013; Kelemu et al. 2015).

Prominent pioneers in edible insect research include Gene R. De Foliart, Julietta Ramos-Elorduy, Paul Latham, François Malaisse and Arnold van Huis, who have published widely and advocated for insect consumption by humans in almost all parts of the world. While many scientists have focused on specific taxonomic groups (e.g., caterpillars), some have focused on specific regions or communities.

In Africa, eating insects is a popular custom and has long made sense. Thomas Risley Odhiambo, one of the founders of the African Association of Insect Scientists (AAIS), used the term 'mini livestock' to emphasise the need to integrate edible insects into conventional food systems and to develop mass-rearing techniques for the continuous supply of insect proteins for food and feed. Some of the countries on the African continent where eating insects is widely practised are the Democratic Republic of the Congo, Republic of Congo, the Central African Republic, Cameroon, Uganda, Zambia, Zimbabwe, Nigeria and South Africa, but data on the levels of quantities of insect biomass produced and consumed, vis-à-vis the ecosystems, are scarce.

The most eaten insects include saturniid caterpillars, termites, crickets, grasshoppers and palm weevil larvae. Applied research on edible insects is somewhat in its infancy stage, with only a few practical applications being translated into benefits. A few cases have demonstrated that small enterprises that rear edible insects could be upgraded to medium- and large-scale firms for international trade. However, considering Africa's food and nutritional insecurity, more research and innovations are needed in various edible insect value chains to fully reap the benefits of edible insects.

To date, most edible insects are harvested from the wild, with species being referred to by vernacular names that depict morphological features, host plants, or the seasons in which they occur. Although new species are being discovered, little research has been done into mass production, sustainable wild harvesting, processing, nutritional profiling, safety analysis, post-harvest handling, packaging and branding of insects, and the viability of insect-based products as alternative nutrient-rich foods and feed additives.

Another important fact is the global outcry that has arisen about the decline of insect biodiversity; as Hallmann et al. (2017) reported that the biomass of flying insects in protected areas declined by more than 75% in 27 years. Added to this is the fact that current biodiversity conservation efforts, unfortunately, seem to overlook insects. Thus, there is a need for strong policies and a sound regulatory framework to be put in place to use insects sustainably. Since policies are usually inspired by religion, culture, and tradition, documenting indigenous knowledge among different communities would be valuable for promoting entomophagy. Understanding the diversity, bio-ecology, and indigenous practices regarding the use of edible insects is critical in a changing climate.

A decade ago, limited policies promoted insects as food or feed, mainly derived from various examples in Europe and Asia or inspired by the Codex Alimentarius. However, over the last few years, there has been a spike in promoting edible insects by food-conscious lobbies, the private sector, and scientists globally. Uganda and Kenya have taken the lead on the African continent in establishing standards for the use of insects as food and feed (International Development Research Centre 2019; Kenya Bureau of Standard 2020; Uganda National Bureau of Standard 2019). The International Centre of Insect Physiology and Ecology (*icipe*) based in Nairobi, Kenya has been very instrumental in the development of these standards and other technological innovations, capacity building and advocacy for insects for food, feed and other uses in sub-Saharan Africa. These efforts earned *icipe* the Curt Bergfors Food Planet Prize, 2020. In the European Union, insect proteins that are produced according to the

conventional livestock regulations are approved for use in fish feed (Costa-Neto and Dunkel 2016), and most recently, the larvae of the yellow mealworm (*Tenebrio molitor*) have been endorsed for human consumption (IPIFF 2021).

This special issue was initiated under the auspices of AAIS, following its 23rd scientific conference held in Abidjan, Côte d'Ivoire, between 18th and 22nd November 2019. After this event, the 1st *Ruspolia* symposium was held in Nairobi, Kenya, on 11th December 2019. In the same vein, the Agriculture for Food Security 2030 (AgriFoSe2030; www.slu.se/agrifose) had held the first African Conference on Edible Insects in Harare, Zimbabwe, in August 2019. All these events and other initiatives on the continent presented rich forums for discussion, exchange and learning on new advances in insects as food and feed in Africa and beyond. However, scientific conferences scarcely provide full details of the studies and do not assure quality through a peer-review process. Therefore, it was imperative to consolidate these presentations and new findings into a special issue for dissemination to a broader audience to inform stakeholders on new frontiers and stimulate debate and collaboration within Africa and beyond. Over 65 scientific papers from several countries, worldwide, were submitted, of which about 40 from 15 countries from Africa, Asia, South America and Europe were accepted and published.

Overview of this special issue: advances in insects for food and feed in Africa and beyond

Theme 1: Biology, ecology and mass production of edible insects

In many communities around the world, edible insects are mainly harvested from the wild by using rudimentary traps. The contribution by Sengendo et al. (2021) is a cost–benefit analysis of an improved trap recently developed by the same team for harvesting wild swarms of edible long-horned grasshopper *Ruspolia differens* (Serville) in Uganda. The new trap comprises light-emitting diode lamps used with collection drums fitted with funnels to retain the catch, and meshes to filter non-target insects. This improved trap was compared with traditional commercial traps which use mercury lamps–that are potentially hazardous to the environment–together with open-ended collection drums, which are inefficient in retaining the trapped grasshoppers. The authors found that the improved trap, which minimises the collection of non-target insects and poses minimal risks to human and environmental health, was more profitable than the traditional traps were. The authors highly recommend scaling up this new trapping technology as a replacement to the traditional harvesting method.

Babarinde et al. (2020) stressed the scarcity of successful large-scale edible insect farms in Africa, despite the vast biodiversity of species, favourable atmospheric conditions, and abundance of potential insect feed in the continent. The authors suggest intensified empirical investigation of the ecological impact of insect farming, economics, species biology, and processing aspects to guide potential insect producers and processors.

So far, farming the black soldier fly (BSF) *Hermetia illucens* L. for bioconversion of waste into nutrient-rich larvae as an alternative source of protein additive for animal feed is increasingly gaining momentum in Africa and beyond. The by-product of waste bioconversion from BSF farming is an excellent biofertiliser. The performance of BSF on different waste streams under diverse conditions is a subject of continuous research. Adebayo et al. (2021) evaluated the development and nutritional composition of BSF larvae on commercially available organic waste streams in Lagos, Nigeria, including brewery waste, food remains, and fruit wastes. Their results indicate that, although all the substrates were suitable for the mass rearing of BSF, marked variations were noted in the development and nutritional content of BSF larvae produced from the different substrates. They concluded that manipulating waste types could help to produce BSF larvae with specific nutrient values for specific industry needs.

Douan et al. (2020) studied morphological changes in eggs of the nutrient-rich, popularly farmed house cricket *Acheta domesticus* L. during incubation. They noted easily distinguishable egg features at specific stages of incubation, such as pigmentation, cerci, length, width, and volume, which could help in controlling the breeding process. More of these types of studies must be done regarding various other edible insect categories of interest.

Driving the insects for food and feed agenda requires expanding the range of edible insects that can be commercially mass-reared. Moreover, the evaluation of insects for mass rearing mainly occurs under well-regulated laboratory conditions, which are not practically maintainable by most resource-poor smallholder farmers. Ganguly et al. (2020) investigated the potential of mass production of the short-horned grasshopper *Spathosternum prasiniferum prasiniferum* Walker for feeding livestock in India under ambient conditions. Their results show that a single pair of this grasshopper could produce 66,326 individuals or approximately 4 kg per year. This finding is an excellent motivator for starting small-scale commercial production of the grasshopper for livestock feed by resource-poor farmers who cannot procure environmental control chambers.

The review by Molina-Vega et al. (2021) highlights the significance of two *Agave salmiana* Otto ex Salm-Dyck infesting edible insects, *Comadia redtenbacheri* Hammerschmidt and *Aegiale hesperiaris* Walker, as food in Mexico.

These insects are rich in nutrients and are highly accepted by Mexicans due to their exquisite flavour. However, their potential is limited, primarily by their seasonal availability. In addition, there are reports of depletion of the insects due to overexploitation and habitat change.

Puzari (2020) reviewed the prospects of entomophagy, noting that profit margins of insect farming can exceed those derived from grains. The review draws attention to feed, geographic location, and climatic conditions as critical factors influencing insect mass rearing. It cautions against overlooking the risk of accidental release of farmed insects into the environment and/or transformation of these insects into invasive species. The author emphasises the need for risk assessment and proper legislation when developing insect farming ventures.

Theme 2: Nutritional, medicinal and nutraceutical value of edible insects

Data on nutrient composition continue to play a central role in publications on edible insects, which was the case for this special issue. By using standard techniques, various authors have reported nutritional values of insects not previously analysed. While these data continue to be made available, there is a need to harmonise protocols and sampling procedures for the nutritional analyses of edible insects.

At the beginning of 2019, the Horn of Africa was hit by the most devastating desert locust swarm in decades that arose because of good breeding conditions in the recession areas, including storms. This offered another opportunity where many locusts could be collected and analysed for their nutritional contents. Kinyuru (2020) evaluated the nutrient composition of these ravaging pests and found that adults contained almost 50% protein, with calcium being the most abundant mineral. The study further investigated the oil composition of the locust, which showed high oleic acid amounts and excellent physicochemical properties. The oil stability indices (peroxide and iodine values) were within acceptable limits, which the food industry can exploit. The author recommended that locust control efforts should include harvesting them for food and feed as an alternative management strategy.

Soren et al. (2021) studied the nutritional and mineral compositions of two edible cricket species, *Tarbinskiellus portentosus* Lichtenstein and *Schizodactylus monstrosus* Drury, consumed by the Bodo tribe in Assam, India. They found that the protein value of both crickets – which are readily available all the year round – was comparable (51–57%), although *T. portentosus* contained more fat than *S. monstrosus* did.

Kinyuru et al. (2021) evaluated the acceptability of cereal-cricket-formulated porridge against the traditional cereal porridge by nursery school children in Gishu, Kenya. The nutrient-rich and microbially safe cricket-enriched porridge was administered at 300 ml daily to 138 children for four weeks. Based on their study, porridge with a 5% cricket powder supplement was deemed to confer the best sensory attributes. The study demonstrated that crickets could be used to develop nutritious, acceptable, and affordable food for school-going children. The paper also showed that consumer acceptability of the cricket-porridge increased during the intervention. The authors recommended using flavour enhancers to improve the flavour of the cricket-based porridge, which they believed would invariably improve the overall acceptance of the porridge.

Food composition tables, which various stakeholders might consult for the nutritional value of edible insects in Africa, are still scarce. Therefore, Weru et al. (2021) systematically reviewed and collated nutritional data on insects from Africa to determine if they contained sufficient nutrients for human consumption. Using search engines such as Scholar, PubMed, SCOPUS and Web of Science, the authors generated 483 articles, and after three iterations of screening, they finally extracted data from 26 of them. The paper lists the insects that are most consumed in Africa, which are dominated by the order orthoptera (locust, crickets, and grasshoppers). It further establishes the fact that edible insects have variable amounts of nutrients. Additionally, their review echoes several studies on insects as an essential source of macronutrients (especially proteins) and mineral elements (iron, zinc, and magnesium) necessary for human health. They note that edible insects could be appropriate to use for mitigating micronutrient deficiencies associated with these minerals. The dearth of further studies being carried out on the antinutritional attributes of edible insects, vitamin analyses, and the bioavailability of these valuable nutrients comprise one of the key gaps highlighted by this review.

Theme 3: Processing, food fortification and feed formulation with edible insects

In sub-Saharan Africa, edible insects are traditionally processed to improve the sensory attributes they present and their shelf-life through steaming, roasting, smoking, frying, stewing, toasting, among other methods. Various technologies have been developed to increase consumer interest, for instance, using insects in ingredients such as powders or flour. These technologies include drying and new processing techniques designed mainly to extract and maintain protein, fat, and chitin integrity. Insect-based ingredients are nutritious foods for the general population and specialised vulnerable groups and animals. In this special issue, authors have focused on developing novel processing technologies for providing a sustainable approach to improving the consumption of insects as food and/or feed.

Adepoju and Ajayi (2020) investigated consumption patterns of the edible termite *Macrotermes bellicosus*

Smeathman and its acceptable use in complementary foods. The study found that consumption of the termite was dependent on its availability during the rainy season. Furthermore, the authors found that the enrichment of sorghum pap with *M. bellicosus* enhanced its sensory attributes and acceptability.

Traditional processing affects insects differently, partly due to differences in processing parameters, as shown by Tinarwo et al. (2021) when they evaluated the effect of heat-processing methods on the nutritional value of *Henicus whellani* Chopard. Dry and wet heat treatments affected the nutrient contents differently, based on time–temperature combinations, indicating that the proper processing of the insect increases the availability of healthy animal protein and dietary fibre. The study recommends specific time–temperature combinations for insect processing to yield nutritional values suitable for humans.

Blending insect meals with other ingredients improves the nutritional value of the final product; however, care must be taken not to affect the sensory attributes of the final product. Musundire et al. (2021b) in Zimbabwe formulated an extruded instant porridge composed of termite and millet powders and characterised its physicochemical, nutritional, and sensory attributes. The study was premised on the fact that nutritious termites have been traditionally blended with cereal flour, targeting malnourished populations. Most of the individuals who participated in the study liked the termite-containing porridge, although a sizable number indicated that unfavourable mouth stickiness, heavy termite aroma, and fear of allergic reactions were some of the challenges that reduced acceptance. The authors stressed that such an instant porridge could help to address micronutrient deficiencies if its attributes are improved to enhance consumer acceptability.

Adeboye et al. (2020) aimed to introduce the consumption of insects in a non-traditional form by producing a ready-to-cook soup powder made from the white butterfly *Clerodendrum volubile* (a medicinal plant) and the termite *M. bellicosus* in various ratios. The termite content increased the protein content of the soup powder, with the soup comprising 10% termites being the most acceptable.

Insects have been used as a source of protein in animal feed and have been reported to result in similar growth, weight gain, feed intake and feed conversion when compared with non-insect protein-based feeds. Similar findings were reported by Elangovan et al. (2021) in their work that explored the suitability of black soldier fly (BSF) prepupae as poultry feed with corn-soy as a control diet. They concluded that BSF could play a significant role in converting waste into feed and add to the feed basket in the future. Moyo et al. (2021) evaluated the effect of meal made from the mopane worm *Imbrasia belina* Westwood on meat composition, oxidative stability and fatty acid profile of broiler chicken meat. They concluded that insect meal significantly increased the protein content of breast meat and omega-3 fatty acid content of thigh meat. Bakar et al. (2021) studied the effects of BSF prepupae oil (BSO) on the growth performances, digestibility, fatty acid composition and haematological parameters of tilapia fish upon partial replacement of conventional fish oil (FO) with BSO. Their results showed that FO could be successfully replaced with 25% BSO in tilapia diets without affecting fish growth performances and palatability.

Theme 4: Safety of food and feed based on edible insects

Although edible insects have immense nutritional benefits, they may harbour exogenous and endogenous risks to human and animal health. Potential food safety hazards associated with edible insects may be grouped into three broad categories: microbiological hazards, chemical hazards, and allergies as reported by Ng'ang'a et al. (2021). These food safety concerns have immensely hampered the acceptability of insects as food and/or feed, particularly in developed countries. Currently, there is finite knowledge on the safety of edible insects, particularly in developing countries. Thus, Ng'ang'a et al. (2021) reviewed safety issues associated with wild-collected and reared grasshoppers used as food or feed. Some of the risks identified by the authors are those associated with microbiological and heavy metals in wild-harvested *R. differens* and other edible grasshoppers. They compared levels of contaminants in the edible grasshoppers and minced meat, which is a comparison recommended in many parts of the world as a yardstick for measuring food safety in edible insects. The study found high microbial counts, including total viable counts, *Enterobacteriaceae* and lactic acid bacteria, yeasts and moulds, and bacterial endospores exceeding maximum limits. However, conventional processing methods were effective in reducing microbiological hazards, except for bacterial endospores. Moreover, foodborne pathogens, including *Salmonellae*, *Listeria monocytogenes* and *Escherichia coli*, were not detected in *R. differens* processed samples. Low accumulations of lead and chromium in wild-harvested *R. differens* were reported in Uganda.

Musundire et al. (2021a) evaluated the influence of soil composition and colour on the mineral composition of soldiers of the fungus-growing termite species *Macrotermes natalensis* Haviland. The authors found higher lead contents in termites obtained from yellowish-brown soil than those from dark-grey, grey, brown and light-grey soils. On the other hand, the contents of copper and zinc in soil were positively correlated with copper and zinc in insects; and inversely correlated with lead levels. The study concluded that there is a possible risk of lead poisoning associated with consumption of the soldier *M. natalensis*; however, the risk

is more pronounced in insects harvested from yellowish-brown soils. Soren et al. (2021) reported finding heavy metals in two edible crickets (*T. portentosus* and *S. monstrosus*) collected from local markets in India. Although the study detected arsenic, lead and cadmium in both cricket species, the levels were within the recommended maximum limits for other foods such as meat; therefore, the crickets were deemed safe for human consumption. The authors attributed the accumulation of these heavy metals to anthropogenic pollution and recommended that strict measures be put in place to stop the environmental pollution.

Elechi et al. (2021) assessed the bioaccumulation of heavy metals (cadmium, chromium, copper, lead and zinc) in prepupae of black soldier fly (BSF) that were cultured on chicken mash and various types of organic wastes (food waste, brewery waste, and fruit waste). The study showed that bioaccumulation was more likely to occur in brewery waste than in the other substrates, while bioaccumulation was reported for three (copper, lead and chromium) of the five heavy metals. Nevertheless, all heavy metal levels reported in the study were within safe limits for animal feeds when using organic waste recommended for rearing BSF larvae over chicken mash.

The food safety concerns in terms of heavy metal contents suggest that quality control measures should be implemented to ensure good hygienic practices are followed during wild collection, rearing, handling, processing, and storage of edible insects and their products. Furthermore, it is important to put a legislative framework in place, especially in developing countries, for edible insect production, commercialisation, trading, and the need for safety criteria specifically tailored for edible insects. This is likely to boost consumer confidence and ease global trade in this commodity.

Theme 5: Cross-cutting issues: socioeconomics, climate change and policy

This special issue provides a wealth of new knowledge by documenting recent cutting-edge research on the development of captive rearing of edible insects, rather than relying on dwindling seasonal wild harvests; improvements in technologies for the wild harvesting of edible insects for sustainability; and new insights into the nutritional value of edible insects such as their nutraceutical potential; among other things.

In Kenya, Nyangena et al. (2020) reviewed the effects of climate change on agriculture and animal production and its potential long-term effect on nutrition and health. The team extrapolated their analysis on some edible insects, considering their presumed sensitivity to habitat change, erratic rainfall, and temperature rises. They opined that climate change would have an impact upon insect consumption by affecting the swarming of grasshoppers, termites, and lake flies in the Lake Victoria region.

One way to ensure sustainable use and avoid seasonal wild harvesting of edible insects is to farm them. This requires knowledge and the mastery of quality control parameters. In the Lake Victoria region, insects such as crickets have been promoted since 2013 for their richness in macro- and micro-nutrients and capacity to improve the livelihoods of rural families. Before that, farming crickets was generally unknown to many African communities. Halloran et al. 2020 conducted a pilot study in the Nyanza district in Kenya to determine the drivers of awareness and interest in adopting cricket farming. They found that cricket farming was still relatively unknown in the area, and its adoption was low among rural smallholders due to various factors such as awareness, ownership of a mobile phone, and the degree of risk averseness. A follow-up study by Oloo et al. (2021) reported that most cricket farmers were females between the ages of 30 and 49 years, with four years of experience in cricket farming and secondary-level education. They described several factors that influenced awareness, including a farmer's socioeconomic status, which might also impact on the adoption of cricket farming. Cricket farming provided a monthly income of USD 50. Both Halloran et al. (2020) and Oloo et al. (2021) have suggested that various socioeconomic factors should be considered when transferring cricket farming technology.

In Uganda, Olum et al. (2020) assessed the influence of food neophobia and socio-cultural factors regarding the consumption by, and the willingness of, consumers to consume three edible insects. Their findings are very informative in terms of understanding the "yuck" or disgust factor. They confirmed previous findings that emphasised the role of education and social status on the willingness to consume insects. The choice and decision to consume a specific type of insect find their root in culture and habits. The promotion of insect consumption should consider aspects such as familiarity with specific edible insects among potential consumers. Babarinde et al. (2020) confirmed similar findings in Nigeria, where the consumption of insects remains unpopular among urban dwellers, particularly among the elites, unlike rural dwellers who embrace entomophagy. Ibitoye et al. (2020) reported a similar trend in the Oyo state in Nigeria, where indigenous edible species were most preferred, with insect consumption declining among the youth. The authors found that gender and educational level were crucial determinants of insect consumption. Factors such as nutritional and medicinal benefits and the influence of family members reportedly promoted insect consumption. Kekeunou et al. (2021) conducted a study on the edible grasshopper *Oxycatantops spissus* Walker, in Cameroon. Unlike many edible insects that are seasonal, this grasshopper is abundant throughout the year and is found in cassava *Manihot esculenta* Crantz and maize *Zea mays* L. fields. Cultural habits and

good taste were the main drivers of the consumption of this grasshopper. Generally, poor hygiene, ignorance of nutritional benefits, cultural barriers, and personal insect phobia were among the factors that hindered insect consumption. Given insect neophobia in Uganda, Nigeria, and Cameroon, the studies concluded that awareness on nutritional benefits of edible insects might improve their acceptability by people.

Despite the rich diversity of edible insects reported in Africa, limited reports are available on specific species consumed in other parts of the world. Moreover, aspects such as regulating and legislation on edible insects are still at the infancy stage on the African continent. Given their importance as a vital source of protein for humans and animals and supplementing other by-products, there is a need to develop guidelines for the entire edible insect value chain. Although Nigeria is the most populous country in Africa, there are no policy guidelines in place for the consumption, upscaling and commercialisation of insects. Hence, Usman and Yusuf (2020) investigated the diversity of edible insects in Nigeria and provided a pathway for creating an environment that would enhance consumer confidence and attract investment in the sector, including a proposed legislative and regulatory framework.

Next directions in the development of a value chain for edible insects in Africa and beyond

Theme 1: Biology, ecology and mass production

Whereas the contributions in the current special issue highlight significant advances in understanding the biology, ecology and mass production of edible insects, further research is required to realise a vibrant edible insect industry. Apart from the commercial production of the black soldier fly, there is limited scaling up of most techniques for improved wild harvesting and mass rearing of other edible insects. Moreover, work on developing these techniques for a vast majority of edible insects has not yet started. A more vigorous investigation of the biology and behaviour of edible insects is required to guide the acceleration of mass production and provide a better understanding of the factors affecting their population dynamics, which is required to design strategies for checking dwindling harvests and species extinction. The implementation of biosafety measures and legislation should seriously be considered to avert the risk of mass-reared edible insects turning into invasive pests. The role of manipulating the rearing substrate to produce insects with specific nutritional attributes is an area that needs more detailed research, especially on commonly used edible insects with great potentials, like mopane worms and grasshoppers, which are largely harvested from the wild, although catches are becoming unpredictable.

Theme 2: Nutritional, medicinal and nutraceutical value of insects

Data on anti-nutrients continue to be lacking, while analyses of amino acids and vitamins are scarce. The role of different processing methods in affecting nutrient quality and the occurrence and quantification of process contaminants will be a good direction to follow for research in this niche. Furthermore, the evaluation of the functional properties of insect fractions to be used as food ingredients in the food industry is still lagging. In a broader sense, studies on aspects of insects regarding nutraceuticals and medicines are still in their infancy. Therefore, further research is needed to isolate bioactive compounds in edible insects to test and verify their therapeutic functions, as reported in several indigenous communities.

Theme 3: Processing, food fortification and feed formulation with edible insects

Although further research is required on the value addition of *R. differens*, it is undisputed that they represent a sustainable food resource. Major hurdles impeding the development of the sector still include legal barriers and an assumed lack of consumer acceptance of the products. Both issues could be overcome with the help of sound scientific knowledge on the beneficial properties and safety risks of edible insect species and the development of effective and scientifically proven safety procedures, together with the communication of the relevant information to both consumers and policymakers.

Fortifying the common staples with nutritious insect products is an avenue that needs further research to ensure that the products are nutritious and acceptable to consumers. The application of modern food processing technology in the development of new products and processes is still underexplored. Attention should, therefore, be given to evaluating how edible insects can fit in, especially in the production of special products from insects for specific interest groups such as those with dietary requirements. With the development of national standards regarding the use of insects as food and feed, the concomitant development of commercialisation and mass production will need to progress in collaboration and partnership with the private sector.

Theme 4: Safety of edible insect-based food and feed

Studies on the safety of edible insects are still limited or nonexistent regarding certain aspects, especially in Africa. So far, the unculturable fraction of the insect microbial community and its importance in food safety are particularly unexplored. Thus, the characterisation of the bacterial community in

edible insects is necessary, using more state-of-the-art techniques, such as whole-genome sequencing for bacteria and sequencing of the internal transcribed spacer region (ITS) of the nuclear DNA for fungi, to identify foodborne pathogens. Moreover, a more in-depth characterisation of the fungal community and assessment of the prevalence of mycotoxins in edible insects are needed. The development of new techniques to reduce spore populations and prevent germination of spores while still maintaining nutritional quality and texture of edible insects should be explored further. Another angle of safety where research effort has been minimal is the analysis of edible insects for safety from chemical contaminants such as agricultural chemicals and heavy metals.

Theme 5: Cross-cutting issues: socioeconomics, climate change and policy

This special issue has highlighted outstanding innovations in insects as food, feed, attitude and disgust factors. Therefore, further effort is needed to sensitise and create awareness around consuming insects and the comparative advantages compared with conventional foods. Besides providing food or feed, edible insects are part of cultural and religious practices in many communities and could be extended to include sustainability in the broader scheme of things. Since taste is cultural, the processes that have led to the acceptance of, and the values attached to numerous species of edible insects must be documented to develop suitable policies and promote insects as food and feed.

In Africa, Kenya and Uganda stand as role models in establishing standards for the use of insects as food and feed. Given the rising demand for protein, it is expected that other countries will also adopt similar approaches.

It is a known fact that there is currently a global decline in insect biodiversity, mainly due to climate change and anthropogenic activities leading to forest decline and habitat change. Since insects are at the centre of the ecological food chain and edible insects form the focus of this special issue, we do not address the broader relationship between climate change, habitat change, and biomass availability. Accordingly, this special issue does not specifically address how insects could provide a vehicle towards attaining the United Nations Sustainable Development Goals in Africa. We believe that edible insects could serve as indicators of ecosystem health because of what they represent in the environment and their relevance as food and feed.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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