



Post-harvest handling, processing and value addition of edible insects as a sustainable food resource in Africa: A review

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Abstract

Edible insects at different developmental stages like larvae, pupae and adults serve as food resources across the globe. They are rich in nutrients such as protein, fat, essential vitamins and minerals. Since recent decades, there is a growing interest in utilising edible insects as part of the sustainable solutions to malnutrition and food insecurity in the world. This review analyses the current advances in post-harvest processes and value addition in edible insects, focusing on development of modern processing technologies, use of insects in food enrichment in order to improve their nutritional profile, palatability as well as extraction of high value industrial products/compounds from the insects. Presently, most edible insects are harvested from the wild and traditionally processed through boiling, roasting, frying, smoking, solar drying, stewing, steaming, drying and pounding or a combination of these methods. To increase consumer interest in insects, various novel technologies have been developed particularly aiming at using insects as ingredients in a non-recognizable form, such as powders or flour to enrich and supplement food products. Insect-based bakery products such as bread, biscuits, muffins, crackers, cookies, complementary food and porridges are the most common products. The most popular insects reported in food enrichment include crickets, winged termites, mealworms, palm weevil larvae, locusts, and grasshoppers. Technologies for extraction of insect components like chitin, fat/oil, and protein for application as ingredients in food industry are still being developed. Conventional food products with 5% insect powder inclusion are highly acceptable to consumers in Africa.

Keywords Processing · Food enrichment · Insect products

Introduction

Entomophagy, the practice of eating insects is widespread across various cultures with differences based on geographical location, species of insects and specific ethnic groups (Raheem et al. 2019; Raubenheimer & Rothman 2013). Currently, over 2205 insect species are consumed in 128 countries around the world, with the highest number of species (932) in Asia, followed by North America (especially Mexico) and Africa (Omuse et al. 2024). Edible insects are among the natural, sustainable, and renewable food resources that is considered as an option for alleviating food and nutrition insecurity (Verneau et al. 2021). Edible insects can be produced sustainably and with a much smaller ecological footprint than most vertebrate livestock, such as cattle and swine (Ooninx et al. 2010; Wegier et al. 2018). The effectiveness is a result of the diversity of insects, their high fecundity, feed conversion efficiency, and their ability to recycle a variety of organic materials into edible insect

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biomass while emitting fewer greenhouse gases (Nakagaki & Defoliart 1991; Oonincx et al. 2010, 2015; van Huis & Oonincx 2017). Moreover, most edible insects provide adequate energy and protein in the human diet and also meet the amino acid requirements of the human body (Rumpold & Schlüter 2013). Most edible insects are also rich in essential fatty acids that are required by the human body (Guil-Guerrero et al. 2018; Otero et al. 2020); and trace elements, including copper, iron, phosphorus, selenium, and zinc, and they also contain vitamins like riboflavin, pantothenic acid, biotin, and folic acid (Akullo et al. 2018a; Gere et al. 2019; Weru et al. 2021).

The current world population of 7.3 billion is expected to reach 9.7 billion in 2050 and 11.2 billion in 2100 (DESA-UN, 2015). This population increase will necessitate a 100% increase in food production (Belluco et al. 2013). There is also a corresponding reduction in the amount of land that can be used to cultivate that food, which is anticipated to be exacerbated by climate change (Van Huis, 2013). It is predicted that low-income countries might experience the harsh effects of climate change and food insecurity, including widespread malnutrition and poverty (FAO, 1996). Therefore, global improvements in socioeconomic conditions and the availability of food are required (Lange & Nakamura 2021). The dwindling source of animal proteins, coupled with the fact that one-third of the world's population consumes insects as part of their traditional diet, is creating industrial interest in insects as food in most parts of the world (Dossey et al. 2016; Raheem et al. 2019).

In Africa, the demand for edible insects is growing mainly because the animal source protein, which is a superior source of protein is increasingly becoming expensive and scarce (Niassy et al. 2016). Additionally, there is a growing demand for nutritious, safe, and healthier food alternatives such as insects (Payne et al. 2016; Weru et al. 2022). With this trend, more and more people are likely to be involved in insect rearing, both at small-scale and medium-scale levels, to supplement the harvesting of insects from the wild (Raheem et al. 2019). This development is likely to lead to mass production of edible insects as raw materials for whole foods and food ingredients (El-Shanshoury 2014; Imathiu 2020; Kinyuru et al. 2018).

Post-harvest handling, processing and value addition to insects are prerequisites for obtaining high quality and microbiologically safe raw materials, ingredients, and products for large-scale insect food and feed manufacturing applications (Ojha et al. 2021). This is particularly important because insects are perishable as a result of high water activity and high amounts of free amino acids, polyunsaturated fatty acids, and nutrient content (Guil-Guerrero et al. 2018; Otero et al. 2020; Rumpold & Schlüter 2013). Many technologies for processing raw materials have been developed to eliminate potential safety hazards such as pathogens

(Ng'ang'a et al. 2019). These technologies also aim at preserving or improving the nutritional value, organoleptic (taste, texture, color, aroma), and functional qualities of the food/food ingredient (Akullo et al. 2018a, 2018b; Bouarab Chibane et al. 2019; Khatun et al. 2021). This is particularly important because insects are already being utilized to produce a range of novel products that come in several forms, such as powders, pastes, liquids, and oils (Babarinde et al. 2021; Burt et al. 2020; Tao & Li 2018).

Proper processing and value addition are important factors for consideration for incorporating edible insects into more conventional meals at all scales, including large-scale industry, cottage industry, restaurant, and professional cuisine, as well as at the household level (Dossey et al. 2016). Suitable food processing and value addition techniques are necessary for the realization of the full nutritional benefits of edible insects. Several studies have reported on the current technologies of processing raw edible insects to food and as ingredients for food applications, however, this information is scattered and fragmented. Moreover, contradicting information exists on the effect of processing and value addition on the nutrient quality and sensory acceptability of insect-based products. Therefore, this review aimed to consolidate the current scientific knowledge on post-harvest practices and processing techniques of edible insects and their effect on nutrient quality, with emphasis on insects as ingredients in food products enrichment and novel insect ingredients for diverse food applications.

Materials and methods

This study reviewed the literature on post-harvest handling and value addition to edible insects, particularly in African countries. A search of the use of insects for food fortification and the different products fortified was conducted. Online databases that were used in the review included Google Scholar (<https://scholar.google.com/>), Scopus (<https://www.scopus.com/>), PubMed (<https://pubmed.ncbi.nlm.nih.gov/>) and Web of Science (<https://apps.webofknowledge.com>). Searches were done using the following keywords: 'edible insects', 'edible insect processing', 'insect for food', 'insect as food ingredient', 'edible insect harvesting', 'post-harvest handling of insects'. Other relevant scientific studies were obtained through a cross-referencing approach. The abstracts of the different studies were first screened to determine whether they fit into the review and/or to eliminate duplicate articles.

The full versions of these articles were evaluated according to an established criterion. The inclusion criteria were: studies conducted on edible insects in African countries; studies reporting insect source (collection from the wild or farmed); the preprocessing and processing techniques; the

effect of processing on nutrient quality; use of insects as ingredients in food enrichment or fortification, and novel ingredients extracted from insects. Additionally, the studies had to be published in English in a peer reviewed journal or book. The articles reporting on the use of insects for fortification were screened to include only studies that defined the insect species, forms of insect ingredients, enrichment levels, nature of the final products, and how enrichment affected the quality of nutrients as well as the sensory acceptability of the final product.

Results and discussion

Characteristics of the studies

Geographical distribution of studies

Most studies (8/25) reported on the post-harvest handling of different species of termites, 6 on grasshoppers, 4 on crickets and 2 on locusts, black soldier fly and palm weevil (Fig. 1a). The highest number of studies (16/25) were from East Africa; Kenya (8), Uganda (6), Congo (2) and Tanzania (1). The higher number of publications emerging from East Africa could be attributed to the increasing recent consumer interest in alternative and healthy source of animal protein (Weru et al. 2022); coupled with the fact that insects are a traditional diet to most communities in East Africa (Kinyuru & Ndung'u, 2020).

Products and insects in food enrichment

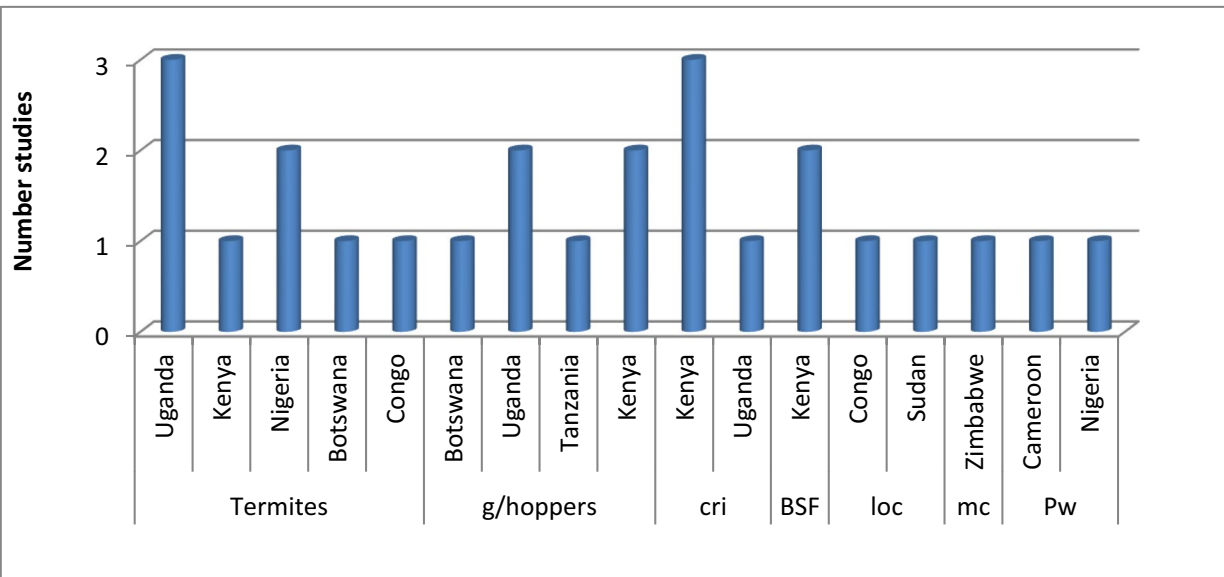
Products enriched with edible insects were diverse in nature, with bakery product (15/27) being the most common study, followed by complementary food (5) and porridge (3) (Fig. 1b). Among the countries reporting on food enrichment using insects, Kenya (11) was the most predominant, followed by Nigeria (9), Ghana (3) and Uganda (2). Cricket, termites, palm weevil and silkworm pupae food enrichment was the most common. This finding is in agreement with (Amoah et al. 2023). This could be due to the availability of the respective insects, coupled with the knowledge of their nutritional content compared to other insects. Powder was the most common form of insect used in food enrichment, probably due to their ease of handling and versatility which promote incorporation into different products (Kamau et al. 2017).

Post-harvest handling and traditional processing of edible insects and their effect on nutrients

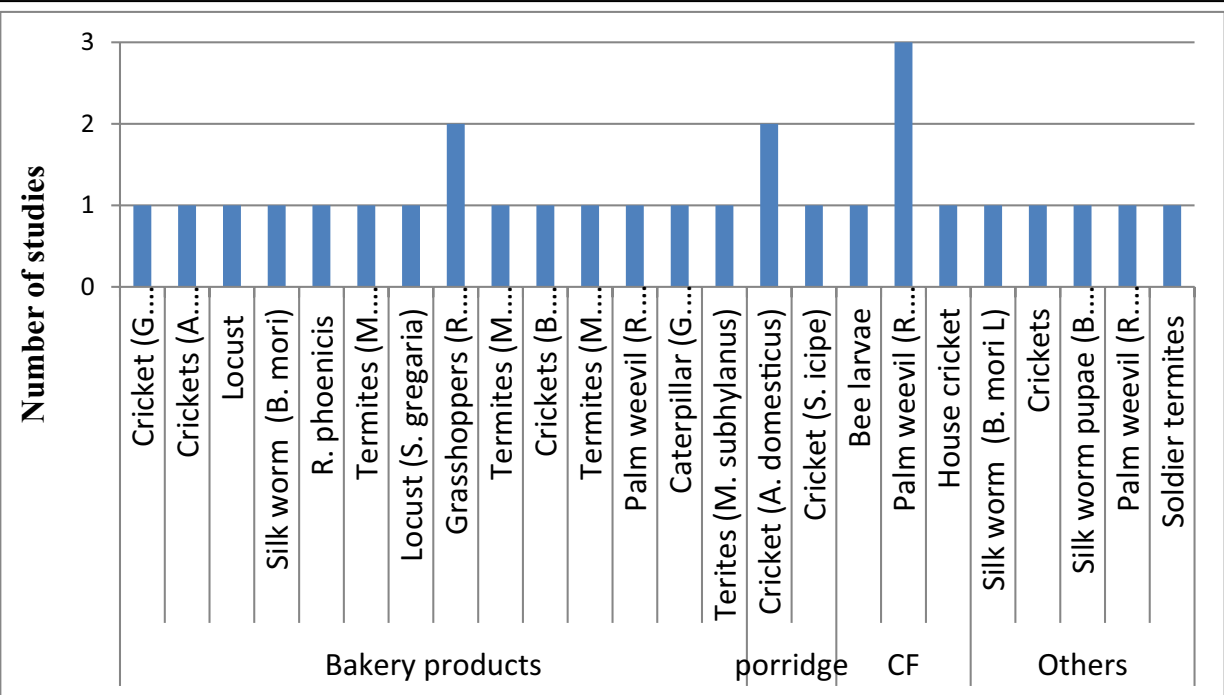
Local and traditional knowledge of harvesting, handling and processing of edible insects forms a good background

for scientific knowledge and can contribute to the adoption of modern production and processing techniques for edible insects (Melgar-Lalanne et al. 2019). A large variety of edible insects at various stages of development are collected within the traditional and cultural practices of small scale producers in sub Saharan Africa (Akullo et al. 2017a, 2017b; Ishara et al. 2022; Kusia et al. 2021; Mmari et al. 2017; Wanjala et al. 2023). Harvesting, post-harvest handling and processing practices have been passed on from generation to generation (Akullo et al. 2017a, 2017b) and are found to be largely common in insect consuming communities with slight variations (Mmari et al. 2017). These practices are mainly influenced by the species of edible insect, morphological characteristics, stage of development at harvesting (egg, larvae, pupa, or adult), local knowledge and practices, and the purpose of processing (whether for preservation or for direct consumption) (Ishara et al. 2022). A summary of the most commonly applied methods of collection/harvesting, post harvesting treatments, and processing practices are given in Table 1. The most common pretreatments include cleaning in water, removing unpalatable elements such as the head, gut, wings and legs; blanching in hot water or boiling. The main forms of processing can be summarized as wet heat treatments such as steaming and boiling, dry heat treatments including sun drying, toasting, roasting and oven drying, frying, freeze drying and smoking.

Boiling followed by sun drying is a method that is used for preserving large quantities of edible insects for consumption at a later date after harvest (Illgner & Nel 2010). Sun drying is the most popular technique for preserving edible insects at the household level, given its low energy input and affordability. Termites are prepared by boiling for a few minutes the morning after the swarm, and then they are spread out on mats, iron sheets, or sacks to dry in the sun for 3–4 days depending on the weather (Ayieko et al. 2010). Boiling deactivates the insect enzymes while drying reduces the moisture content of fresh products by thereby transforming them into more stable products. Drying preserves food by lowering its water content to between 10 and 15 percent, which makes it less susceptible to microbial deterioration and enzymatic degradation (Melgar-Lalanne et al. 2019). Water activity (*aw*) is directly correlated with microbial growth (*aw*). At *aw* < 0.65 most microorganisms stop growing, but when water conditions are favorable they can resume growth (Grabowski & Klein 2017a, 2017b). A reduction of free water increases the dry matter concentration significantly without damaging the tissues or changing the physical appearance of foods and is an important step for food ingredient extraction (Lamidi et al. 2019). Boiling followed by drying are significant processes in the production of insect powders.



a Studies reporting on post-harvest handling of insects



b Studies reporting on Insect based products and insect used in the enrichment

Fig. 1 Summary of studies retrieved (Cri = cricket, BSF = black soldier fly, loc = locust, Mc = mopane caterpillar, palm weevil, CF = complementary food)

Table 1 Post-harvest handling methods and traditional processing of different edible insect species in Africa

Scientific name	Common name	Country	Source and method of collection	Pre-processing	Processing	Reference
<i>Macrotermes bellicosus</i>	Termites	Uganda	Wild collection by attraction to light from spear grass	Washing in cold water to remove soil	Boiling and sun drying, followed by pounding to paste and mixed with either ground-nut paste and honey	(Akullo et al. 2017a, 2017b)
Termites	Termites	Uganda	Collected from the wild during swarming	Cleaning to remove foreign material	Steamed or smoked in banana leaves; sometimes only the heads eaten	(Van Huis 2003)
<i>Syntermes soldiers</i>	Soldier termites	Uganda	Harvested from the termite mound	Washing in cold water	Fresh termites pounded to paste and cooked as meat balls	(Akullo et al. 2017a, 2017b)
<i>Macrotermes subhyalinus</i>	Termites	Kenya	Winged termites collected from the wild by attraction to bright light	Removing of wings and foreign material	Toasting in its own oil followed by sun drying,	(Kinyuru et al. 2010)
<i>Macrotermes bellicosus</i>	Termites	Nigeria	Adult winged termites collected from the wild	Removal of wings and cleaning	Roasted and salted or ground into a cake	(Ekpo et al. 2007)
<i>Macrotermes nigeriensis</i>	Termites	Nigeria	Adult winged insects collected from the wild	Removal of wings and cleaning	Washed, salted, mildly fried or roasted without oil; also eaten raw	(Igwe et al. 2011)
<i>Hodotermes mossambicus</i>	Harvester Termites	Botswana	Winged termites collected during nuptial flight	Removal of head and wing	Roasted in hot ash and sand; pounded into a cake, sometimes eaten raw	(Nonaka 1996)
Termites	Termites	Congo	Winged termites collected from the wild	Removal of wings	Fried in own fat	(Van Huis 2003)
<i>Ruspolia differens</i>	Grasshoppers	Botswana	Adult grasshoppers collected from the wild		Roasted in hot ash and sand after removing head and intestines, sun-dried before storage; pounded to powder, and eaten with porridge	(Nonaka 1996)
<i>Ruspolia differens</i>	Grasshoppers	Uganda	Adult grasshoppers collected from the wild	Removal of antennae, legs and wings	Frying	(Van Huis 2003)
<i>Ruspolia differens</i>	Grasshoppers	Uganda	Adult grasshoppers collected from the wild	Removal of legs and appendages	Boiling, oven roasting	(Ssepuuya et al. 2020)
<i>Ruspolia differens</i>	Grasshoppers	Tanzania	Adult grasshoppers collected from the wild	Removal of the wings and appendages	Boiling followed by either smoking, toasting, deep frying, sun drying	(Mmari et al. 2017)
<i>Ruspolia differens</i>	Grasshoppers	Kenya	Adult grasshoppers collected from the wild	Plucking of the wings and cleaning	Toasted in own fat and dried	(Kinyuru et al. 2010)
<i>Ruspolia differens</i>	Grasshoppers	Kenya	Adult grasshoppers collected from the wild	Removal of foreign materials and washing with chilled tap water	Boiling, toasting, solar drying, oven drying	(Nyangena et al. 2020a)

Table 1 (continued)

Scientific name	Common name	Country	Source and method of collection	Pre-processing	Processing	Reference
<i>Acheta domesticus</i>	Crickets	Kenya	Adult house crickets reared on a mixture of brewer's waste and kales	Removal of foreign materials and washing with chilled tap water	Boiling, toasting, solar drying, oven drying	(Nyangena et al. 2020a)
<i>Acheta domesticus</i>	Crickets	Kenya	Adult crickets obtained from a rearing centre	Blanching in boiling water for 5 min	Solar drying and grinding to powder	(Kamau et al. 2017)
<i>Acheta domesticus</i>	Crickets	Kenya	Crickets obtained from the rearing unit	Blanching	Solar drying	(Ayieko et al. 2016)
<i>Brachytrupes</i> spp.	Crickets	Uganda	Adult crickets collected from the wild	Blanching in hot water and removing the wings	Pan frying, oven drying	(Akullo et al. 2018a, 2018b)
<i>Hermetia illucens</i>	Black soldier fly	Kenya	Pre-pupae reared on a mixture of brewer's and kitchen waste	Removal of foreign materials and washing with chilled tap water	Boiling, toasting, solar drying, oven drying	(Nyangena et al. 2020a)
<i>Hermetia illucens</i>	Black soldier fly	Kenya	Larvae obtained from a farm	Washing in cold water	Boiling followed by drying	(Kamau et al. 2018)
<i>Locust migratoria</i>	Locust	Congo	Adult locust from the wild	De-winging	Roasting or frying	(Ishara et al. 2022)
<i>Anacridium melanorhodon</i>	Tree locust	Sudan	Adult stage collected from the wild	De-winging	Boiled or fried	(El Hassan et al. 2008)
<i>Gonimbrasia belina</i>	Mopane caterpillar	Zimbabwe	Collection from the wild population	De-gutting and washing	Boiling, roasting, sun drying, frying	(Manditsera et al. 2022)
<i>Rhynchophorus phoenicis</i>	Palm weevil	Cameroon	Laval stage collected from the market	Killed by freeze drying	Oven dried at 50°C for 72 h and ground to flour	(Womeni et al., 2012)
<i>Rhynchophorus phoenicis</i>	Palm weevil	Nigeria	Collected from a local farmer	Sorted to remove dead ones, gutted and washed	Roasted	(Adepoju & Ayenitaju 2021)

Effect of processing on nutrient quality of edible insects

The rich nutritional composition of edible insects is well covered in literature (Rumpold & Schlüter 2013; Van Huis et al. 2021). Insects are rich in protein and fat with a good amino acid and fatty acid profile and a high variety of micro-nutrients such as vitamins, minerals and useful bioactive compounds (Rumpold & Schlüter 2013).

Protein quality measures such as essential amino acids scores, and in vitro digestibility, level of antinutritional factors, bioaccessibility/bioavailability of trace elements such as vitamins and minerals are also other nutritional factors that have been used in assessing the nutritional quality of insects and effects of processing on the insects (Baek et al. 2019; Kinyuru et al. 2010; Kröncke et al. 2018; Musundire et al. 2016). In this review the effects of various conventional processing practices on these nutritional factors are explored.

Protein content, in-vitro digestibility and amino acids profile

Baek et al. (2019) analysed the effect of freeze drying at -15°C for > 30 h, boiling at 100°C for 10 min, steaming at 100°C for 30-min, oven broiling at 180°C for 11 min, deep frying at 250°C for 2 min, pan frying at 250°C for 2 min and microwaving for 2.5 min on the nutritional composition of reared meal worms (*Tenebrio molitor* L). Freeze drying resulted in the highest level of crude protein (55.23%), while wet heating (boiling and steaming) had significantly lower crude protein content on wet basis (16.16% and 21.14%), respectively. Pan frying (49.20%) and deep frying (38.94%) had the lowest crude protein content on dry matter basis. Adepoju & Ayenitaju (2021) observed an increase in protein content from 14.38% to 49.20% when palm weevils were roasted and dried while Manditsera et al. (2022) observed an increase in crude protein when mopane caterpillars were boiled for 20 min and then dried at 40°C (49.4%) as compared to samples processed by boiling (48.83%). Ssepuuya et al. (2020) reported that boiling of *Ruspolia differens*, had an insignificant increase in crude protein with minimal effect on the amino acid profile while oven roasting had no effect. Blanching of edible beetle grubs *Oryctes* spp, at 100°C for 5 min resulted in a significant decrease in crude protein content, but minimal effect on the amino acid profile (Maimba et al. 2023); while roasting and toasting increased the protein content (Muthee et al. 2024). This was attributed to the increase in the dry matter content and possible decrease in the fat proportion of the sample.

The effect of processing differed with the species of edible insects and their morphology. Degutted insects seem to have more protein loss when exposed to wet heating which

is attributable to exposure of the inner parts of the insects to leaching (Maimba et al. 2023; Manditsera et al. 2022). On the other hand, whole insects such as termites and grasshoppers had a significantly lower losses of proteins (Nyangena et al. 2020b; Ssepuuya et al. 2020). The duration and temperature of the heat treatment also influences the crude protein levels especially in dry heat processes, like toasting and deep frying leading to a higher reduction of protein when compared to oven drying in lower temperature ranges (Baek et al. 2019; Manditsera et al. 2022; Ochieng et al. 2022). This could be attributed to increase in protein content due to removal of water and concentration, but to an optimum above which subsequent protein breakdown occurs due to protein changes at higher temperatures such as denaturation, oxidation, and volatilization. There is therefore a need for more studies on the optimization of heat treatment regimens for edible insects where the nutritional composition of the insects is preserved.

In vitro protein digestibility (IVPD)

For in vitro digestibility of proteins under various processing methods, such as; cooking, boiling, frying, oven drying, roasting, different procedures are used, making direct comparison of results difficult. The in in-vitro protein digestibility of raw yellow mealworms (85.0%) was increased by vacuum cooking (90.5%), boiling (90.1%), and 15 and 30-min oven cooking (91.5% and 90.4% respectively); while frying (87.2%) had no effect (Caparros Megido et al. 2018). Kiiru et al. (2020a, 2020b) reported an increase in in- vitro protein digestibility for raw (29–30.0%) and extruded (38–50%) cricket blended flours. Bosch et al. (2016) found that freeze-dried insects had IVPD ranging from 76.4% to 93.3% in a canine model. The digestibility for specific insects were as follows: house crickets (91.7%), yellow mealworms (91.3%–92.5%), black soldier fly larvae (89.7%), and black soldier fly pupae (77.7%). Kinyuru et al. (2010a) also reported high in- vitro protein digestibility (82.3 to 90.5%) for freshly caught termites (*Macrotermes subhylanus*) and grasshoppers (*Ruspolia differens*) that declined slightly after solar drying at approximately 30°C . The authors also observed that the IVPD was comparable (90.11% to 90.46%) for different termite subspecies but differed significantly for the grasshoppers. For tree locust, the IVPD of boiled and fried locusts was 49.89% and 41.13%, respectively showing that frying significantly reduced the IVPD (El Hassan et al. 2008).

When subjected to a denaturing temperature during heat processing, insect protein digestibility can increase. This allows digestive enzymes to act on the unfolded polypeptide chain. However, excessively high temperatures can reduce protein digestibility by causing amino acid reactions that hinder enzymatic digestion (Opstvedt et al. 2003). It was

observed that antinutritional factors contribute to a reduction in IVPD. For example, toasting and boiling tree locust increased the tannins and phytates content, leading to a further lowering of in vitro digestibility. This is possibly due to the complexing of these antinutritional factors with proteins, rendering them inaccessible to proteinases (El Hassan et al. 2008). It is thus observed that both the insect species and the processing methods have an effect on protein in vitro digestibility.

Lipids and lipid profiles of edible Insects

The lipid profile of edible insects includes phospholipids, triglycerides, sterols, waxes, and lipolytic vitamins. Phospholipids and triglycerides are the most dominant components of lipids (Kolobe et al. 2023). Triglycerides consist of fatty acids and glycerol, with fatty acids comprising saturated fatty acids (SFAs) and unsaturated fatty acids (USFAs). The unsaturated fatty acids are further divided into mono-unsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs) (Akullo et al. 2018a, 2018b). In previous studies, it has been shown that palmitic acid, stearic acid, and arachidonic acid are the most common SFAs, while palmitoleic acid and oleic acid are the most common MUFAs; and linoleic (n-6) and eicosapentaenoic acids are the most commonly found PUFAs (Kinyuru 2021). The accumulation of lipid and fatty acid contents in different insect species depends on a combination of factors such as species type, sex, reproduction stage, developmental stage, living temperature, season, feed substrates, geographical origin, and processing methods as well as biological factors including enzymatic activity (Akullo et al. 2018a, 2018b; Baek et al. 2019; Mutungi et al. 2019).

Nyangena et al. (2020a, b) found that different processing methods had significant effects on fat content in four edible insect species: *Hermetia illucens*, *Acheta domesticus*, *Spodoptera littoralis*, and *Ruspolia differens*. Toasting, boiling, oven-drying, and solar-drying reduced fat content by 42.0%, 15.0%, 6.1%, and 2.7%, respectively. The fat loss order among the insect species was *H. illucens* (24.2%) > *A. domesticus* (15.3%) > *S. littoralis* (13.6%) > *R. differens* (12.8%). Fat loss correlated positively with the fat content of the raw insects. Ochieng et al. (2022) compared the effects of processing (blanching at 100 °C for 5 min, boiling at 100 °C for 15 min, toasting at approximately 150 °C for 10 min and deep frying in preheated vegetable cooking oil at 175 °C), the levels of PUFAs α -linolenic acids (Omega 3), linoleic acid (Omega 6) and arachidonic acid (Omega 6) were 1.3–3.2-fold higher in blanched *R. differens* than in boiled, toasted and deep-fried samples. Furthermore, as the levels of PUFAs decreased from blanching > boiling > toasting > deep-frying, there was a proportional increase in the SFAs. This can be attributed to decomposition of different

PUFAs to SFAs during processing. Besides, the high temperature increases the vulnerability of the double bonds in PUFAs to attack by free radicals, resulting into their significant decrease after heating (Abbas Ali et al. 2017).

The lipid oxidation produced by the different drying processes negatively affects lipid quality and even the quantity (availability) of fats present in edible insects. Tiencheu et al. (2013) observed that sun-drying caused an increase in the peroxide value of *R. phoenicis* larvae oil especially if the larvae were previously boiled. Further, Fourier transform near-infrared spectroscopy (FTNIR) also demonstrated that when an *R. phoenicis* larvae oil is subjected to heating or dehydration, the initial nature of the triglycerides changes significantly and the decrease in the level of unsaturation is evidence of a transformation occurring in the fatty acids within the oil, thus indicating a modification in the oil's nutritional value. Similarly, freeze drying of mealworms oxidized the lipid fraction when compared with other drying techniques such as rack-oven-drying and microwave-drying, resulting in high 4-hydroxy-2-nonenal (4-HNE) concentration in the freeze dried samples (Kröncke et al. 2018). During processing of *Polyrhachis vicina* Roger, an edible black ant by sun drying, other organic molecules detected including aldehydes were formed whereas ketone levels dropped while hydrocarbons and hydrolytic rancidity products were detected in trace amounts (Li et al. 2009). All these studies show that the interaction of processing technique and insect's species is of significance in the quantity and quality of edible insect fat/lipids, hence, the ultimate nutritional content is a function of insect species and processing method.

Crude fibre content of edible insects

Crude fibre increased or decreased depending on processing method and insect species (Manditsera et al. 2022; Mutungi et al. 2019; Ochieng et al. 2022). Boiling reduced whereas toasting increased the crude fibre levels (Nyangena et al. 2020a). The decrease in fibre content during boiling could be associated with some of the complex carbohydrates being dissolved or were washed off the tissues while dry high heat treatments like toasting, on the other hand concentrate these polysaccharides, especially with the concomitant loss of fat during the process (Muthee et al. 2024). Thermal treatment may also result in an increase in total fibre by causing the formation of protein-fibre complexes. Unlike boiling and toasting, solar drying did not affect crude fibre contents of *A. domesticus* and *R. differens* (Nyangena et al. 2020a). Crude fibre also includes chitin and complex carbohydrates such as cellulose and lignin that might be present in the insects' gut (Madibela et al. 2007). Therefore the pre-processing of insects involving degutting, cleaning and removal of parts (legs, wings, head) or starvation prior to processing could

be a source of variability in crude fibre content (Mutungi et al. 2019).

Minerals content and bioavailability

According to Nyangena et al. (2020a, 2020b), the ash contents of *H. illucens*, *A. domesticus*, *S. littoralis* generally decreased upon boiling but increased in the toasted products possibly due to concentration effects. Toasted *R. differens* had comparatively higher phosphorus (P) levels than in the blanched, boiled and deep-fried samples (Ochieng et al. 2022). The lower levels of phosphorus in blanched, boiled and deep-fried *R. differens* could be as a result of leaching of the mineral into the processing medium (Ssepuuya et al. 2020). Minerals such as calcium (Ca), magnesium (Mg), and zinc (Zn) levels were also significantly higher in wet heat treatments (boiled and blanched) (Mutungi et al. 2019; Ochieng et al. 2022; Ssepuuya et al. 2020). The stability of Ca and other minerals during diverse thermal processing in foods could be linked to their association with proteins and chitin in insects (Ssepuuya, et al. 2020). It was further observed that deep frying that resulted in lowest protein content when compared to other treatments also had the lowest mineral compositions (Ochieng et al. 2022). Similarly, the fried Sudanese tree locusts contained higher levels of K and lower levels of P, whereas the levels of Ca, Na, Fe, Mg, Zn and Co in the boiled or fried products did not differ. However, percent extractability (potential bioavailability) of Ca, K, Fe, Zn, and Co were higher in the fried locusts while extractabilities of Na and Mg were higher in the boiled ones (El Hassan et al. 2008).

In a previous study by Manditsera et al. (2022), several treatments including (a) raw, (b) boiling for 30 min, (c) boiling for 60 min, (d) pan roasting, (e) boiling 30 min followed by (f) pan roasting were evaluated on beetle (*Eulepida Mashona*) and cricket (*Henicus whellani*). The study found that the difference in the iron and zinc content for both insects was not significantly different among the treatments. A significant difference in the mineral solubility was reported between the beetle and cricket. In addition, boiling of beetles significantly reduced the percentage mineral bioaccessibility of iron, sulphur and zinc, while the roasted samples had significantly lower zinc bioaccessibility compared to raw samples. The differences in mineral bioaccessibility between insect species could be related to the insect matrix. During processing, bivalent minerals form interactions with other food constituents such as protein and carbohydrates and thus decrease the bioaccessibility (Mutungi et al. 2019). Insoluble dietary fibre binds iron and zinc thereby reducing their bioaccessibility (El Hassan et al. 2008). Previous studies showed that crickets had a higher chitin content than beetles (Manditsera et al. 2018).

Vitamins

Unprocessed insects are a very good source of riboflavin (vitamin B₂), niacin, pantothenic acid, pyridoxine (vitamin B₆), biotin, folic acid, and cyanocobalamin (vitamin B₁₂) (Oonincx & Finke 2021). Low levels for some of these vitamins occasionally reported in the literature are likely due to losses during processing and storage. Solar-drying of grasshoppers and termites resulted in significant loss of riboflavin (29–46% loss), folic acid (47–66%), niacin (6–26%), pyridoxine (9–13%), retinol (30–56%), ascorbic acid (25–55%), and α -tocopherol (9–30%) (Kinyuru et al. 2010). The rate of the vitamin destruction is accelerated by heat, as some vitamins are very volatile and heat sensitive. Furthermore, water soluble vitamins as well as other beneficial bioactive compounds can be lost through leaching effects in wet heat-treatments such as boiling (Musundire et al. 2016). The loss in the water-soluble and fat soluble vitamins content may also be as a result of oxidation on exposure to light and heat effects of the processing temperatures (Kinyuru et al. 2010). Vitamins are also lost due to enzymatic and chemical degradation, especially in the presence of traces of heavy metal ions, which positively catalyzes the chemical degradation (Mutungi et al. 2019).

Insects as ingredients in food enrichment

Researchers have suggested integrating insects into currently available food products to increase the acceptability and consumption of insects and insect-based foods. This improves the nutritional quality and the sensory quality (in some foods), while also easily masking the physical characteristics of the insects (Amoah et al. 2023; Melgar-Lalanne et al. 2019). According to Dossey et al. (2016), the most optimum insect-based ingredient form for most products is powder. Insects are processed to powder by spreading thoroughly cleaned insects out on a lightly greased oven trays and drying according to the procedures by Fröhling et al. (2020), the adequately dried insects are then milled to powder. It is possible to properly blend insect powders with a variety of different ingredients without compromising the structural integrity or texture of the final product (Dossey et al. 2016). Depending on the processing technique, powders can have a light color, mild flavor, aroma (Akullo et al. 2017a, 2017b), which can have a minimal impact on the finished product. Based on packaging and storage conditions, powders have a long shelf life compared to other forms of insect products, ensuring the ease of bulking. Additionally, powders mix well with any product even though the final product might not be dry (Kamau et al. 2018).

The focus of most recent study has been on using edible insects to fortify more conventional food types like biscuits, bread, cookies, pasta, burgers, and sausages, boosting their

nutritional content (Melgar-Lalanne et al. 2019). A literature search on different databases found 25 articles reporting the fortification of various food products with edible insects across several African countries. Particular attention was paid to the studies that defined insect species, forms of insect ingredients, enrichment levels, nature of the final products, and how enrichment affected the quality of nutrients and the sensory acceptability of the final product as summarized in Table 2.

Bakery products enriched with edible insects

Biscuit and cookies are well-known cereal food products, which are popular among both rural and urban people. Their popularity is attributed to affordability, palatability, availability, and long shelf life (Adeola & Ohizua 2018; Farzana et al. 2022). The convenience of the biscuit dough mix makes it possible to incorporate other ingredients, which eventually improves the nutrient profile (Arama et al. 2023). The primary ingredient of these cereal products is wheat hence they supply more energy and less of other nutrients. Incorporating insect flour into the biscuit dough mix enhances the nutritional value of the final product, in addition to influencing the sensory characteristic. For instance, biscuits enriched with 5, 10, 15 and 20% cricket (*G. bimaculatus* and *A. domesticus*) powder exhibited increased protein, fat, fibre and mineral contents than the wheat based biscuits which did not contain insects (Arama et al. 2023). In addition, the cricket based biscuits were well accepted among pre-school children in Kenya compared to the wheat biscuits. However, the overall acceptability in cricket fortified biscuits were higher than the control among the adult consumers (Duku et al. 2023). Homann et al. (2017) reported developing a cricket-based biscuit suited for school feeding programs and testing the biscuits' acceptance among Kenyan school children. In comparison to a similar biscuit with milk, the results showed that the cricket biscuits had a high level of acceptability and that their organoleptic qualities were above average. Akande et al. (2020a, 2020b) explored the possibility of replacing skimmed milk with locust and silk worm (*B. mori*) powder in the formulation of a high energy biscuit. The biscuits enriched with 15% insect powder had relatively similar proximate compositions to the skimmed milk biscuits and the biscuits met the expected minimum standards for high energy biscuits (USAID, 2016), and all the samples received good sensory rankings from panelists. Traditionally, aid organizations worldwide use cereals and dried milk as the primary ingredients in high-energy biscuits intended for relief feeding. Utilizing insects in the formulation of relief food in Africa is noble and innovative as insects form part of the cultural diet in most African communities (Ishara et al. 2022; Kelemu et al. 2015).

In Ghana, a supplemental palm weevil (*R. phoenicis*) larvae and orange-fleshed sweet potato biscuit was developed to improve the nutrition of pregnant mothers (Ayensu et al. 2019). Calcium, iron, and zinc levels of the biscuits increased with increasing levels of palm weevil larvae flour substitution, and acceptability among the pregnant mothers was high. Awobusuyi et al. (2020) formulated cookies composed of whole grain sorghum meal and termite meal mixed at a 3:1 ratio w/w sorghum: termite to form a sorghum–termite meal blend. This blend was used to partially substitute wheat flour at 20%, 40%, and 60% (sorghum–termite blend: wheat flour (w/w)). The cookies blended with sorghum–termite meal had about twice the quantity of protein, minerals, and amino acids compared to 100% wheat flour. However, the increased substitution level of the sorghum-termite blend led to a decreased spread factor of the cookies. Ochieng et al. (2023a, 2023b) investigated the impact of four processing methods on volatile compounds from insect-based cookies to provide insights on consumer acceptance. There was a greater resemblance of sensory characteristics between control cookies (100% of wheat flour) and those fortified with 10% deep-fried *R. differens*. Cookies fortified with blanched and boiled *R. differens* meal expressed higher digestibility (80.41% and 78.73%, respectively) that was comparable to the control (88.22%). The influence of processing methods on aroma compounds is important for process modifications that produce pleasant aromas. In a related study, Ogidi et al. (2023) developed cookies from wheat flour fortified with a blend of edible mushrooms (*Termitomyces robustus*) and different insects to address micro- and macronutrient deficiencies. The fortified cookies exhibited improved nutritional, bio-functional and health-promoting properties. In particular, cookies with *T. robustus* and *Rhynchophorus ferrugineus* had the highest protein, crude fiber, iron, potassium, and magnesium contents, while the wheat cookies fortified with mushroom and *Branchytrupes membranaceus* had the highest zinc content (625.02 mg/100 g).

Cheseto et al. (2020) identified the potential volatiles and fatty acids that contributed to the aroma and taste of cookies baked with insect oils compared with the olive and sesame oils. Consumers' acceptance was high for cookies baked with *R. differens* (95%) and sesame (89%) oils compared to those with olive and *Schistocerca gregaria* oils. Utilization of edible insect oils in cookies could be a strategy to entice people toward entomophagy by decreasing insect-based food product neophobia, thereby increasing consumer acceptability of the baked products. Ouma et al. (2022) substituted wheat flour with caterpillar (*Gonimbrasia zambesina*) powder in the formulation of muffins and the finding showed that the nutrient content and in-vitro digestibility of the 10% insect enriched muffins were above that of the control. A similar trend of nutrient enrichment was observed

Table 2 Edible insects as ingredients for food product enrichment

No	Insect species	Form and amount of insect used in formulation	Final product	Effect of formulation on the nutritional quality	Acceptability of final products	Country	Reference
1	Cricket (<i>Gryllus bimaculatus</i>)	Cricket powder (5, 10, 15, 20%) + wheat flour	Biscuits	Cricket biscuits exhibited 1.2–1.7, 1.1–3.7, 1.2–3.0 and 1.1–1.2-folds higher ($p < 0.05$) protein, ash, fiber, and fat, respectively. Ca, Fe, and Zn were 1.1–3.7, 1.1–1.2 and 1.4–4.0-folds higher, respectively	Biscuits with 20% enrichment was well accepted among children	Kenya	(Arama et al. 2023)
2	Crickets (<i>Acheta domesticus</i>)	Powder (0, 10, 15, 20%) + wheat flour and sorghum flour	Biscuits	Addition of the crickets increased the protein, energy value, fat and fibre content	ratings for appearance, aroma, texture, taste and overall were significantly higher in cricket-fortified biscuits compared to non-fortified	Kenya	(Duku et al. 2023)
3	Crickets (<i>Acheta domesticus</i>)	Powder (10%) Wheat flour	Biscuit	Cricket biscuit contained more protein, unsaturated fat and most of the vitamins and minerals than the milk biscuit	Both cricket and milk biscuits were well liked by school going children and all sensory properties were rated above average on the Likert scale	Kenya	(Homann et al. 2017)
4	Locust Silk worm pupae (<i>Bombyx mori</i>)	Powder (15%)	Biscuits	Zn, P and K content were significantly higher in locust powder biscuits followed by skimmed milk biscuits and silk worm pupae biscuits Fe contents of both insect-enriched biscuits were above the minimum standard	Sensory scores of biscuits with 15% insect enrichment had no significant differences ($p < 0.05$) compared to the skimmed milk biscuits except for aroma	Nigeria	(Akande et al. 2020a, b)
5	Palm weevil <i>Rhynchophorus phoenicis Fabricius</i>	Powder (0, 35, 70%)	Biscuit	Proximate and mineral (Ca, Fe, Zn) composition of biscuits increased with increasing levels of palm weevil larvae flour substitution level. Carbohydrate and crude fibre in biscuits decreased with substitution	Majority of the panellist (> 50%) liked the biscuit very much in terms of the color, sweetness, aroma, and texture. Over all acceptability (> 60% of panellists)	Ghana	(Ayensu et al. 2019)
6	Winged termites (<i>Macrotermes bellicosus</i>)	Powder (5, 10, 15%)	Crackers	Protein, energy, Fe and Zn increased with substitution level	5% substitution had good sensory quality (color, aroma and texture)	Uganda	(Akullo et al. 2018a, 2018b)

Table 2 (continued)

No	Insect species	Form and amount of insect used in formulation	Final product	Effect of formulation on the nutritional quality	Acceptability of final products	Country	Reference
7	Winged termites (<i>M. bellicosus</i>)	Sorghum-termite meal (3:1) substituting wheat flour at 20, 40, 60%	Cookies	Cookies fortified with sorghum and termite had about double the quantity of protein, minerals, and amino acids compared to the control	As the substitution level of the sorghum-termite blend increased, the cookie hardness decreased and color became darker	Nigeria	(Awobusuyi et al., 2020)
8	Grasshoppers (<i>R. differens</i>)	Powder 10% substitution of wheat flour	Cookies	Insect-based cookies containing blanched & boiled <i>R. differens</i> meal exhibited higher digestibility (80.41% and 78.73%, respectively), comparable to control cookies (88.2%). Insect enriched cookies had elevated levels of isoleucine and leucine	Sensory characteristics of control cookies and those enriched with deep-fried <i>R. differens</i> were similar. Overall acceptability of insect-enriched cookies by male and female respondents ranged between 57 and 80%	Kenya	(Ochieng., et al., 2023)
9	Desert locust (<i>Schistocerca gregaria</i>) African bush cricket (<i>Ruspolia differens</i>)	Oil (300 ml), replacing olive and sesame oil mixed with 1300 g of flour and other ingredients in dough formulation	Cookies	Cookies baked with <i>S. gregaria</i> oil had a significantly higher crude protein and lower carbohydrate content than the other cookies	More than 80% of panelists preferred the color of cookies baked with sesame, olive and <i>R. differens</i> . Acceptance of cookies baked with the oils from <i>R. differens</i> was high (89%)	Kenya	(Cheseto et al. 2020)
10	Crickets (<i>Brachytrupes membranaceus</i>) Termites (<i>M. nigeriensis</i>) Palm tree weevil (<i>R. ferrugineus</i>)	Powder (10%) substitution of wheat flour	Cookies	Cookies fortified with insects <i>M. nigeriensis</i> , <i>B. membranaceus</i> , and <i>R. ferrugineus</i> had higher protein contents (11–12.5%) compared to the control (8.47%)	Cookies fortified with edible insects were well accepted by panellists, just as the control. Insect inclusion improved the texture, taste and flavour	Nigeria	(Ogidi et al. 2023)
11	Caterpillar (<i>Gonimbrasia zambesina</i>)	Powder (0, 5, 10, 15, 20%) + wheat flour	Muffins	Significant increase in protein of insect- enriched muffins	Acceptability of 5% substitution was not significantly different from the control	Kenya	(Ouma et al. 2022)
12	Winged termites (<i>M. subulani</i>)	Powder (5, 10, 20%)	Bread (wheat buns)	Substitution significantly increased content of protein, retinol, riboflavin, iron and zinc	5% substitution had similar acceptance to the control	Kenya	(Kinyuru et al. 2009)
13	Soldier termites (<i>M. bellicosus</i>)	Powder (8, 16,24%) substitution of honey	Bread spread	Energy, protein, Fe and Zn content (per 100 g) of spread increased significantly ($p < 0.05$) with increase in the proportion of soldier termite flour	8% substitution improved produced a bread spread with the best attributes of spreadability, flavour and overall acceptability	Uganda	(Akullo et al. 2017a, 2017b)

Table 2 (continued)

No	Insect species	Form and amount of insect used in formulation	Final product	Effect of formulation on the nutritional quality	Acceptability of final products	Country	Reference
	Cricket (<i>A. domesticus</i>)	Powder (5%)	Porridge	Substitution improved protein E% (percentage of energy supplied by proteins) for children (3–5 years)	5% was acceptable to children (3–5 years)	Kenya	(Kinnyuru et al. 2021)
14	Cricket (<i>Scapsipedus icipe</i>)	Powder (10%)	Porridge	Porridge enriched with cricket meal had significantly higher protein (2-folds), crude fat (3.4–4-folds), and energy (1.1–1.2-folds) levels than the Commercial porridge	N/A	Kenya	(Maiyo et al. 2022)
15	Crickets (<i>A. domesticus</i>)	Powder (0%, 25%, 50% and 75%). Substitution of soybean with flour in a composite of maize, wheat and defatted soybean flour	Porridge	Substitution of soybean with cricket flour improved the protein, fibre and fat contents of the flours with increased substitution levels, while carbohydrate contents decreased	The ratings for colour, aroma and taste of cricket-based porridges were higher among women aged 30 years and above, and those with post-primary education	Kenya	(Aboje et al. 2021, 2022)
16	Palm weevil (<i>R. phoenicis</i>) larvae	Palm weevil roasted powder (10, 15, 20%) + fermented maize flour	CFs (paps)	Substitution increased the crude protein, fat, dietary fibre and gross energy content of the products	10% enrichment had the highest sensory score for colour, taste and aroma, 15% ranked highest in texture and overall acceptability	Nigeria	(Adepoju & Ayenitaju 2021)
17	Palm weevil (<i>R. phoenicis</i>) larvae	Palm weevil roasted powder (10, 15, 20%) + fermented sorghum flour	CFs (paps)	Significant increase in protein, energy, Na, Ca, Mg content with the addition of insect powder	15% substitution had the highest scores for color, taste, texture and overall acceptability	Nigeria	(Adepoju & Ayenitaju 2021)
18	House cricket (<i>Acheta domesticus</i>) Palm weevil larvae (<i>R. phoenicis</i>)	Powder (30%) blending with orange fleshed sweet potatoes (OFSP) at 70%	CFs	OFS-Cricket (20.33 ± 0.58 g/100 g) and Weanimix (16.08 ± 0.13 g/100 g) met the protein requirement of 15 g/100 g from CFs. Although Fe content was significantly higher for OFS Cricket (1.17 ± 0.03 mg/100 g), None of the CFs met the recommended levels for Fe	Between the two OFSP-based edible insect CFs, OFSP-palm weevil was ranked higher for all the sensory attributes compared to the OFSP-cricket Proportion of mothers who liked a lot the porridge from OFSP-cricket (27.6%) or OFSP-palm weevil (37.3%)	Ghana	(Agbemmafe et al. 2020)

Table 2 (continued)

No	Insect species	Form and amount of insect used in formulation	Final product	Effect of formulation on the nutritional quality	Acceptability of final products	Country	Reference
19	Bee larvae (<i>Apis mellifera</i>)	Powder (13%) + Maize (58% and teff (29%)	CFs	Insect based CF recorded the highest fat content (14.3 g/100 g), energy (427.18 kcal/100 g), and vitamins A (706 µg/100 g), B3 (8.2 mg/100 g), and B9 (86.7 mg/100 g)	Sensory acceptability of the insect enriched CF was above average for all parameter, though lower than for the control (commercial wean mix)	Ethiopia	(Mekuria et al. 2021)
20	Termites	Powder (10%) + germinated grain amaranth, maize soy oil and sugar	CFs	Energy, protein, fat and iron were high in termite enriched “Win food” compared to the standard	Crickets blended food had similar liking as the corn soy blend plus (standard)	Kenya	(Konyole et al. 2012)
21	Silk worm pupae (<i>B. mori</i>) African palm weevil (<i>R. phoenicis</i>)	150 g insect paste replacing beef as a filler	Pie & Samosa (snacks)	Protein content of the snacks produced with palm and silk worm compared favourably with the snacks produced with beef fillings Mineral contents of the snack with palm weevil were significantly higher than the other samples	No significant difference in the taste and overall acceptability of samosa snack produced with beef and 150 g insect enriched snacks	Nigeria	(Akande et al. 2020a, 2020b)
24	Crickets (<i>Acheta domestica</i>)	Powder (full-fat and low-fat 15, 30, 45%)	Meat analogue	Protein content was highest (78.60–77.66%) at 15% substitution		Kenya	(Kiiru et al. 2020a, b)
23	Mulberry silk worm pupae (<i>B. mori</i> L)	Powder (5, 10, 15, 20, 25%) substitution of minced fish	Smoked fish paste	Fish paste products with silk worm powder showed significant increase in crude ether extract and caloric value while crude protein content was decreased with insect substitution	5% silk worm enriched product had similar sensory score to the control Addition of silk worm changed the colour and enhanced the cohesiveness and chewiness of all products	Egypt	(Hashem 2022)
24	Melon bug (<i>Coridius viduatus</i>) Sorghum bug (<i>Agonoscelis versicoloratus versicoloratus</i>)	Gelatin 0.5, 1.0%	Ice cream	Total amount of amino acids of insect gelatin was lower than that of the commercial gelatin. The total amount of amino acids of sorghum bug gelatin was higher than that of water melon bug	The ice cream produced using commercial gelatin gave better taste and mouth melt than that with insect gelatin	Sudan	(Mariod & Fadul 2015)

CF complementary food

in termite-wheat buns and termite-honey blended bread spread (Akullo et al. 2017a, 2017b; Kinyuru et al. 2009).

Porridge and complementary foods enriched with edible insects

In sub-Saharan Africa, complementary foods consumed by children and young children are primarily composed of cereal and root tubers which are deficient in essential macro- and micronutrients (Dimaria et al. 2018; Oladiran & Emmambux 2022). Food- to -food enrichment with ingredients such as edible insects, which are locally available is a sustainable strategy for improving the nutrition of children (Halloran et al. 2018; Lange & Nakamura 2021). Kinyuru et al. (2021) developed recipes for porridge consisting of cereal flour and cricket (*Acheta domesticus*) meal, which provided a substantial proportion of the micro and macro nutrients for the children. The overall acceptability of the cricket-based porridge improved with experience in insect consumption, age and level of education of the panelists who participated in the sensory evaluation. Utilization of edible crickets (*Scapsipedus icipe*) meal for the enrichment of flour for porridge production resulted in improved nutrient quality (Maiyo et al. 2022). Palm weevil and bee larvae are among the insects that have been used for enriching the complementary foods resulting to improved nutrient density of the food (Adepoju & Daboh 2013; Agbemaflle et al. 2020; Mekuria et al. 2021). A complementary weaning food made of amaranth and maize grains and supplemented with dagaa fish (3%) and edible termites flour (10%) was evaluated among young children and their mothers in western Kenya, and the result showed a comparable acceptability to the control which had no termite flour (Konyole et al. 2012).

Insects as a meat substitute and in meat alternatives

Incorporating processed edible insects into various snacks provides an innovative strategy to diversify protein sources. This can lead to the creation of alternative food sources and improve the appeal of edible insects in different types of cuisine. Additionally, use of edible insects as replacers of minced beef could be a strategy to bridge the gap in the supply of animal protein as conventional meat production is becoming unsustainable due to the high environmental footprint (Huis & Oonincx 2017). For instance, samosas and pies are among the major snacks in Africa, utilizing beef, chicken, or fish as the major protein fillings in the flour-rich snacks (Akande et al. 2020a, 2020b). Mulberry silkworm pupae and African palm weevil larvae were used as a substitute for the mainstream proteins in snacks (pie and samosa) fillings. The protein content of the cooked snacks enriched with insects compared favorably with the snacks produced with beef fillings, while the fat contents of the snacks were

18% lower than those with beef fillings (Akande et al. 2020a, 2020b). A study by Kiiru et al. (2020a, 2020b) developed a meat analogue by substituting soy protein isolate with full-fat and low-fat cricket (*Acheta domesticus*) meal. The study reported possible development of meat analogues from low-fat cricket. In another study, Mulberry silkworm pupae (SWP) powder was used as a replacer for smoked tilapia fish in processed ready-to-eat fish paste (Hashem 2022). Utilization of the silk worm pupae which is a by-product of the silk industry is important for enhancing a circular production chain that promotes sustainability.

Functional ingredients derived from edible insects

Protein concentrates

New processing technologies for edible insects have been used mainly for protein, fat, and chitin extraction. Protein extraction can be carried out using water, organic solvents, and enzymes to facilitate industrial processes (Séré et al. 2022). The extraction rate and characteristics are species dependent and could influence the extraction yield and the physicochemical, functional, and bioactive properties, depending on the solvent used (Melgar-Lalanne et al. 2019). Ndiritu et al. (2019) extracted proteins from crickets (*Acheta domesticus*) using hexane and aqueous extraction. The protein solubility, water holding capacity, emulsion capacity and stability, foaming capacity and stability and least gelation concentration of the protein concentrates were determined to establish the NaCl and pH at which the functional properties of edible crickets protein concentrates is optimum. Protein solubility of the protein concentrates decreased from pH 2 to pH 8 followed by a significant increase at pH 12. Increase of NaCl concentration to 4% increased the water holding capacity followed by a decline towards 12%. pH had significant effect on the water holding capacity of the protein concentrates ($p=0.024$). Emulsion capacity decreased with increase in NaCl concentration up to 6% followed by an increase with continuous increase in NaCl concentration. NaCl and pH considerably influenced the foaming capacity of the protein concentrates. The least gelation concentration of the protein concentrates was 30%. The protein extraction yield in *Acheta domesticus* was compared using hexane and water in different ratios. Results showed that hexane extraction was more effective for yield, color, crude protein, crude ash, and available carbohydrates. However, water extraction showed better emulsion and foaming capacity, as well as emulsion and foam stability (Ndiritu et al. 2017).

Séré et al. (2022) extracted protein concentrate and isolate from two edible insects; *Brachytrupes membranaceus* and *Macrotermes subhyalinus* in Burkina-Faso. The protein content of the protein isolates ranged from 88.68 to 89.32%, while the protein concentrates varied from 50.96 to

63.82%. The water absorption capacity of *B. membranaceus* and *M. subhyalinus* varied from 3.68 to 1.72 g/g for defatted flour, from 4.68% to 4.11 g/g for protein concentrates, and from 4.51 to 3.43 g/g for protein isolates, respectively. Protein concentrates and isolates of *B. membranaceus* had good functional properties including fat absorption (3.17 to 10.87%) and foaming capacities (39.40 to 49.60%).

Chitin and chitosan

Edible insect chitin is considered as an untapped resource since most edible insects have high amount of chitin (Kouřimská & Adámková, 2016; A. van Huis 2020). Chitin from crustaceans is used in food, pharmaceutical, medical, agricultural and environmental sectors (Melgar-Lalanne et al. 2019). Chitin and chitosan are extracted from the exoskeletons of a variety of edible insects. Ndiritu et al. (2023) compared the functional properties of chitin extracted from house cricket (*Acheta domesticus*), field cricket (*Gryllus bimaculatus*) and black soldier fly cocoons (*Hermetia illucens*) with a commercial shrimp chitin. Chitin extracted from *G. bimaculatus* recorded the highest values in fat absorption capacity (780.14%), emulsion capacity (65.67%) and emulsion stability (65.67%). Chitin extracted from *A. domesticus* was more soluble in water as compared to the commercial chitin. The highest level of deacetylation was reported in *H. illucens* chitin (66.2%) while *A. domesticus* chitin had the least value (47.1%). The commercial chitin and *G. bimaculatus* had the highest values for purity followed by *H. illucens*. In another study, Guarnieri et al. (2022) extracted chitin and chitosan from three developmental stages of *H. illucens*, and showed the antimicrobial activity against *Escherichia coli* and *Micrococcus flavus*, hence demonstrating its potential for different applications.

Insect oils

Laroche et al. (2019) investigated six defatting methods (conventional solvents, three-phase partitioning, and supercritical CO₂) on lipid extraction yield, fatty acid profiles of house cricket (*Acheta domesticus*) and mealworm (*Tenebrio molitor*) meals. Ethanol increased the lipid extraction yield (22.7%–28.8%), irrespective of the insect meal used or the extraction method applied. Supercritical CO₂ gave similar lipid extraction yields as conventional methods for mealworm (*T. molitor*) (22.1%) but was less efficient for *A. domesticus* (11.9%). Tzompa-Sosa et al. (2014) extracted lipids from *Tenebrio molitor*, *Alphitobius diaperinus*, *Acheta domesticus*, and *Blaptica dubia* using three methods: Soxhlet extraction, aqueous extraction, and Folch extraction. *T. molitor* had the highest lipid content among the four species, and the highest extraction yield was obtained with the Folch extraction method. The method used affected the quantity

of lipids obtained as well as the lipid profile. Subsequently, water extraction yielded a high lipid profile quality despite a low yield. Cheseto et al. (2020) compared the chemistry of the oils from two commonly consumed grasshoppers, the desert locust (*Schistocerca gregaria*) and the African bush-cricket (*Ruspolia differens*) with those of olive and sesame oils which are commonly used in bakery products. The results showed that the insect oils were compositionally richer in omega-3 fatty acids, flavonoids, and vitamin E than the plant oils.

Gelatin

Gelatin is a gelling, foaming, and emulsifying agent which can be extracted from mammalian collagen-containing tissues, such as bovine hides and porcine skins. Gelatin is widely applied in the food and pharmaceutical industry (Mariod & Fadul 2015). Gelatin extracted from edible insects has been identified as a potential alternative due to its high availability and low costs (Kim et al. 2020). Chua et al. (2023) investigated the effect of acetic acid pretreatment concentration, time, and centrifugation speed on the yield of black soldier fly gelatin and characterized its physicochemical properties. The results suggested that black soldier fly gelatin can be used as a novel techno-functional ingredient in the food industry. Mariod & Fadul (2015) extracted gelatin from melon bug (*Coridius viduatus*) and sorghum bug (*Agonoscelis versicoloratus versicoloratus*). The dried insect powder was defatted using diethyl ether (samples: solvents, 1: 2) and dried. Insect cakes were then pre-treated with NaCl at various concentrations and gelatin was extracted using hot water, alkali solution or mild acid treatment. The obtained gelatins were characterized by fourier transform infrared spectroscopy (FTIR) and the spectra of insect's gelatin seem to be similar when compared with commercial gelatin.

Conclusion

Majority of the edible insects reported in this study were harvested from the wild and conventional method of processing was reported in most studies. Commonly researched edible insects for food enrichment were crickets, grasshoppers, palm weevil larvae, and silk worm pupae. Nutrient quality of edible insects was affected by the processing techniques applied to the food. Powder was the most common form on insect ingredient incorporated in insect food products. Cookies, biscuits, porridge, and CFs were the most commonly enriched products; 5% insect enrichment was well accepted by consumers with much improved nutritional value especially the proteins and fat. Functional ingredients from edible insects: oils, protein concentrates, chitin and

gelatin have untapped potential. More studies are required on the scope of products fortified, and protocols for extraction of functional ingredients.

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Data availability The data used in this review is available on request.

Declarations

Conflict of interest Authors declare that they have no conflict of interest.

References

- Abbas Ali M, Anowarul Islam M, Othman NH, Noor AM (2017) Effect of heating on oxidation stability and fatty acid composition of microwave roasted groundnut seed oil. *J Food Sci Technol* 54:4335–4343
- Aboge D, Orinda M, Konyole S (2021) Acceptability of complementary porridge enriched with crickets (*Acheta domesticus*) among women of reproductive age in Alego-Usonga sub-county, Kenya. *African J Food, Agricult Nutr Dev* 21(5):18066–18082 (<https://www.ajol.info/index.php/ajfand/article/view/231699>)
- Aboge DO, Orinda MA, Konyole SO (2022) Effect of partial substitution of soybean flour with cricket flour on the nutritional composition, in vitro-protein digestibility and functional properties of complementary porridge flour. *Int J Trop Insect Sci* 42(2):1137–1145. <https://doi.org/10.1007/s42690-021-00629-x>
- Adeola AA, Ohizua ER (2018) Physical, chemical, and sensory properties of biscuits prepared from flour blends of unripe cooking banana, pigeon pea, and sweet potato. *Food Sci Nutr* 6(3):532–540. <https://doi.org/10.1002/fsn3.590>
- Adepoju OT, Ayenitaju AO (2021) Assessment of acceptability and nutrient content of palm weevil (*Rhynchophorus phoenicis*) larvae enriched complementary foods. *Int J Trop Insect Sci* 41(3):2263–2276. <https://doi.org/10.1007/s42690-021-00487-7>
- Adepoju OT, Daboh OO (2013) Nutrient composition of cirina forda (westwood)-Enriched complementary foods. *Ann Nutr Metab* 63(1–2):139–144. <https://doi.org/10.1159/000353885>
- Agbemaflle I, Hadz D, Amagloh FK, Zotor FB, Reddy MB (2020) Orange-Fleshed Sweet Potato and Edible Insects. *Foods* 9:1–14
- Akande AO, Jolayemi OS, Adelugba VA, Akande ST (2020a) Silkworm pupae (*Bombyx mori*) and locusts as alternative protein sources for high-energy biscuits. *J Asia-Pacific Entomol* 23(1):234–241. <https://doi.org/10.1016/j.aspen.2020.01.003>
- Akande OA, Falade OO, Badejo AA, Adekoya I (2020b) Assessment of Mulberry Silkworm Pupae and African Palm Weevil larvae as alternative protein sources in snack fillings. *Heliyon* 6(4):e03754. <https://doi.org/10.1016/j.heliyon.2020.e03754>
- Akullo J, Obaa BB, Acai JO, Nakimbugwe D, Agea JG (2017a) Knowledge, attitudes and practices on edible insects in Lango sub-region, northern Uganda. *J Insects Food Feed* 3(2):73–81. <https://doi.org/10.3920/JIFF2016.0033>
- Akullo J, Agea JG, Obaa BB, Acai JO, Nakimbugwe D (2017b) Process development, sensory and nutritional evaluation of honey spread enriched with edible insects flour. *Afr J Food Sci* 11(2):30–39. <https://doi.org/10.5897/AJFS2016.1463>
- Akullo A, Obaa O-A, Nakimbugwe D (2018a) Nutrient composition of commonly consumed edible insects in the Lango sub-region of northern Uganda. *Int Food Res J* 25(1):159–165
- Akullo J, Nakimbugwe D, Obaa BB, Okwee-Acai J, Agea JG (2018b) Development and quality evaluation of crackers enriched with edible insects. *Int Food Res J* 25(4):1592–1599
- Amoah I, Cobbinah JC, Yeboah JA, Essiam FA, Lim JJ, Tandoh MA, Rush E (2023) Edible insect powder for enrichment of bakery products—A review of nutritional, physical characteristics and acceptability of bakery products to consumers. *Fut Foods* 8(July):100251. <https://doi.org/10.1016/j.fufo.2023.100251>
- Arama D, Kinyuru J, Ng’ang’a J, Kiage-Mokua B, Ochieng BO, Tanga CM (2023) Unraveling the physicochemical attributes of three cricket (*Gryllus bimaculatus*)-enriched biscuit products and implications on consumers’ preference and willingness to pay. *Lwt* 185(April):115171. <https://doi.org/10.1016/j.lwt.2023.115171>
- Awobusuyi et al (2020) Sorghum Insect Composites for Healthier Cookies. *Foods* 9:1427
- Ayensu J, Lutterodt H, Annan RA, Edusei A, Loh SP (2019) Nutritional composition and acceptability of biscuits fortified with palm weevil larvae (*Rhynchophorus phoenicis* Fabricius) and orange-fleshed sweet potato among pregnant women. *Food Sci Nutr* 7(5):1807–1815. <https://doi.org/10.1002/fsn3.1024>
- Ayieko M, Oriaro V, Nyambuga I (2010) Processed Products of Termites and Lake Flies: Improving Entomophagy for Food Security within the Lake Victoria Region. *Afr J Food Agric Nutr Dev* 10(2):2085–2098. <https://doi.org/10.4314/ajfand.v10i2.53352>
- Ayieko MA, Ogola HJ, Ayieko IA (2016) Introducing rearing crickets (gryllids) at household levels: Adoption, processing and nutritional values. *J Insects Food Feed* 2(3):203–211. <https://doi.org/10.3920/JIFF2015.0080>
- Babarinde SA, Mvumi BM, Babarinde GO, Manditsera FA, Akande TO, Adepoju AA (2021) Insects in food and feed systems in sub-Saharan Africa: the untapped potentials. *Springer* 41(3):1923–1951. <https://doi.org/10.1007/s42690-020-00305-6>
- Baek M, Kim MA, Kwon YS, Hwang JS, Goo TW, Jun M, Yun EY (2019) Effects of processing methods on nutritional composition and antioxidant activity of mealworm (*Tenebrio molitor*) larvae. *Entomol Res* 49(6):284–293. <https://doi.org/10.1111/1748-5967.12363>
- Belluco S, Losasso C, Maggioletti M, Alonzi CC, Paoletti MG, Ricci A (2013) Edible insects in a food safety and nutritional perspective: A critical review. *Comprehen Rev Food Sci Food Safety* 12(3):296–313. <https://doi.org/10.1111/1541-4337.12014>
- Bosch G, Vervoort JJM, Hendriks WH (2016) In vitro digestibility and fermentability of selected insects for dog foods. *Anim Feed Sci Technol* 221:174–184
- Bouarab Chibane L, Degraeve P, Ferhout H, Bouajila J, Oulahal N (2019) Plant antimicrobial polyphenols as potential natural food preservatives. *J Sci Food Agric* 99(4):1457–1474. <https://doi.org/10.1002/jsfa.9357>
- Burt KG, Kotao T, Lopez I, Koeppl J, Goldstein A, Samuel L, Stopler M (2020) Acceptance of Using Cricket Flour as a Low Carbohydrate, High Protein, Sustainable Substitute for All-Purpose Flour in Muffins. *J Cul Sci Technol* 18(3):201–213. <https://doi.org/10.1080/15428052.2018.1563934>
- Caparros Megido R, Poelaert C, Ernens M, Liotta M, Blecker C, Danthine S, Tyteca E, Haubruge É, Alabi T, Bindelle J, Francis F (2018) Effect of household cooking techniques on the

- microbiological load and the nutritional quality of mealworms (*Tenebrio molitor* L. 1758). *Food Res Int* 106:503–508. <https://doi.org/10.1016/J.FOODRES.2018.01.002>
- Cheseto X, Baleba SBS, Tanga CM, Kelemu S, Torto B (2020) Chemistry and sensory characterization of a bakery product prepared with oils from African edible insects. *Foods* 9(6):800. <https://doi.org/10.3390/foods9060800>
- Chua LK, Lim PK, Thoo YY, Neo YP, Tan TC (2023) Extraction and characterization of gelatin derived from acetic acid-treated black soldier fly larvae. *Food Chem Adv* 2(April):100282. <https://doi.org/10.1016/j.focha.2023.100282>
- DESA-UNITED NATIONS. (2015). United Nations, World population prospects: The 2015 revision, key findings and advance tables. United Nations, New York.
- Dimaria SA, Schwartz H, Icard-Vernière C, Picq C, Zagre NM, Mouquet-Rivier C (2018) Adequacy of some locally produced complementary foods marketed in benin, Burkina faso, Ghana, and Senegal. *Nutrients* 10(6):785. <https://doi.org/10.3390/nu10060785>
- Dossey AT, Tatum JT, McGill WL (2016). Modern Insect-Based Food Industry: Current Status, Insect Processing Technology, and Recommendations Moving Forward. In *Insects as Sustainable Food Ingredients: Production, Processing and Food Applications* (Issue 7). Elsevier Inc. <https://doi.org/10.1016/B978-0-12-802856-8.00005-3>
- Duku LTT, Orinda MA, Muriithi AN, Aboje DO (2023) Nutritional Composition and Sensory Evaluation of Biscuits Fortified with Sorghum (*Sorghum bicolor*) and Cricket Powder (*Acheta domesticus*) for Improved Food Security. *J Food Stability* 6(1):15–27. <https://doi.org/10.36400/J.Food.Stab.6.1.2023-0022>
- Ekpo KE, Onigbinde AO (2007) Characterization of lipids in winged reproductives. *Pakistan J Nutrit* 6(3):247–51. <https://doi.org/10.3923/pjn.2007.247.251>
- El Hassan NM, Hamed SY, Hassan AB, Eltayeb MM, Babiker EE (2008) Nutritional evaluation and physiochemical properties of boiled and fried tree locust. *Pak J Nutr* 7(2):325–329. <https://doi.org/10.3923/pjn.2008.325.329>
- El-Shanshoury AE-RR (2014) Occurrence of moulds, toxicogenic capability of *Aspergillus flavus* and levels of aflatoxins in maize, wheat, rice and. *Int J Curr Microbiol App Sci* 3(3):852–865
- Farzana T, Hossain FB, Abedin MJ, Afrin S, Rahman SS (2022) Nutritional and sensory attributes of biscuits enriched with buckwheat. *J Agricult Food Res* 10(July):100394. <https://doi.org/10.1016/j.jafr.2022.100394>
- Food and Agriculture Organisation of the United Nations. (1996). *World Food Summit - Final Report - Part I*. <https://www.fao.org/3/w3548e/w3548e00.htm>
- Fröhling A, Bußler S, Durek J, Schlüter OK (2020) Thermal Impact on the Culturable Microbial Diversity Along the Processing Chain of Flour From Crickets (*Acheta domesticus*). *Front Microbiol* 11(May):1–13. <https://doi.org/10.3389/fmicb.2020.00884>
- Gere A, Radványi D, Héberger K (2019) Which insect species can best be proposed for human consumption? *Innov Food Sci Emerg Technol* 52:358–67. <https://doi.org/10.1016/j.ifset.2019.01.016>
- Grabowski NT, Klein G (2017a) Microbiology of processed edible insect products – Results of a preliminary survey. *Int J Food Microbiol* 243:103–107. <https://doi.org/10.1016/j.jfoodmicro.2016.11.005>
- Grabowski NT, Klein G (2017b) Microbiology of cooked and dried edible Mediterranean field crickets (*Gryllus bimaculatus*) and superworms (*Zophobas atratus*) submitted to four different heating treatments. *Food Sci Technol Int* 23(1):17–23. <https://doi.org/10.1177/1082013216652994>
- Guarnieri A, Triunfo M, Scieuzo C, Ianniciello D, Tafi E, Hahn T, Zibek S, Salvia R, De Bonis A, Falabella P (2022) Antimicrobial properties of chitosan from different developmental stages of the bioconverter insect *Hermetia illucens*. *Sci Rep* 12(1):1–12. <https://doi.org/10.1038/s41598-022-12150-3>
- Guil-Guerrero JL, Ramos-Bueno RP, González-Fernández MJ, Fabrikov D, Sánchez-Muros MJ, & Barroso FG (2018). Insects as Food: Fatty Acid Profiles, Lipid Classes, and sn-2 Fatty Acid Distribution of Lepidoptera Larvae. *Eur J Lipid Sci Technol* , 120(6). <https://doi.org/10.1002/EJLT.201700391>
- Halloran A, Flore R, Vantomme P, & Roos N (2018). Edible Insects in Sustainable Food Systems. In *Edible Insects in Sustainable Food Systems* (Issue May). <https://doi.org/10.1007/978-3-319-74011-9>
- Hashem S (2022) Impact of Mulberry Silkworm (*Bombyx mori* L) Pupae Powder on Physicochemical Properties and Consumer Preference of Ready-to-Eat Smoked Fish Paste. *Alex Sci Exchange J* 43(4):571–582. <https://doi.org/10.21608/asejaqjsae.2022.271008>
- Homann AM, Ayieko MA, Konyole SO, Roos N (2017) Acceptability of biscuits containing 10% cricket (*Acheta domesticus*) compared to milk biscuits among 5–10-year-old Kenyan schoolchildren. *J Insects Food Feed* 3(2):95–103. <https://doi.org/10.3920/jiff2016.0054>
- Huis V, Arnold. (2013) Potential of insects as food and feed in assuring food security. *Annu Rev Entomol* 58(June):563–583. <https://doi.org/10.1146/annurev-ento-120811-153704>
- Igwe CU, Ujowundu CO, Nwaogu LA, Okwu GN (2011) Chemical analysis of an edible African termite *Macrotermes nigeriensis*, a potential antidote to food security problem. *Biochem Anal Biochem* 1(105):2161–1009
- Illgner P, Nel E (2010) The Geography of Edible Insects in Sub-Saharan Africa: a study of the Mopane Caterpillar. *Geograph J* 166(4):336–351
- Imathiu S (2020) Benefits and food safety concerns associated with consumption of edible insects. *NFS J* 18(August 2019):1–11. <https://doi.org/10.1016/j.nfs.2019.11.0025>
- Ishara J, Ayagirwe R, Karume K, Mushagalusa GN, Bugeme D, Niassy S, Udomkun P, Kinyuru J (2022) Inventory reveals wide biodiversity of edible insects in the Eastern Democratic Republic of Congo. *Sci Rep* 12(1):1–13. <https://doi.org/10.1038/s41598-022-05607-y>
- Kamau E, Mutungi C, Kinyuru J, Imathiu S, Tanga C, Affognon H, Ekesi S, Nakimbugwe D, Fiaboe KKM (2017) Effect of Packaging Material, Storage Temperature and Duration on the Quality of Semi-Processed Adult House Cricket Meal. *J Food Res* 7(1):21. <https://doi.org/10.5539/jfr.v7n1p21>
- Kamau E, Mutungi C, Kinyuru J, Imathiu S, Tanga C, Affognon H, Ekesi S, Nakimbugwe D, Fiaboe KKM (2018) Moisture adsorption properties and shelf-life estimation of dried and pulverised edible house cricket *Acheta domesticus* (L) and black soldier fly larvae *Hermetia illucens* (L). *Food Res Int* 106(August 2017):420–427. <https://doi.org/10.1016/j.foodres.2018.01.012>
- Kelemu S, Niassy S, Torto B, Fiaboe K, Affognon H, Tonnang H, Maniania NK, Ekesi S (2015) African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. *J Insects Food Feed* 1(2):103–119. <https://doi.org/10.3920/JIFF2014.0016>
- Khatun H, Claes J, Smets R, De Winne A, Akhtaruzzaman M, Van Der Borgh M (2021) Characterization of freeze-dried, oven-dried and blanched house crickets (*Acheta domesticus*) and Jamaican field crickets (*Gryllus assimilis*) by means of their physicochemical properties and volatile compounds. *Eur Food Res Technol* 247(5):1291–1305. <https://doi.org/10.1007/s00217-021-03709-x>
- Kiiru SM, Kinyuru JN, Kiage BN, Marel AK (2020a) Partial substitution of soy protein isolates with cricket flour during extrusion affects firmness and in vitro protein digestibility. *J Insects Food Feed* 6(2):169–177
- Kiiru SM, Kinyuru JN, Kiage BN, Martin A, Marel AK, Osen R (2020b) Extrusion texturization of cricket flour and soy protein

- isolate: Influence of insect content, extrusion temperature, and moisture-level variation on textural properties. *Food Sci Nutr* 8(8):4112–4120. <https://doi.org/10.1002/fsn3.1700>
- Kim TK, Lee MH, Yu MH, Yong HI, Jang HW, Jung S, Choi YS (2020) Thermal stability and rheological properties of heat-induced gels prepared using edible insect proteins in a model system. *LWT* 134:110270. <https://doi.org/10.1016/J.LWT.2020.110270>
- Kinyuru JN (2021) Oil characteristics and influence of heat processing on fatty acid profile of wild harvested termite (*Macrotermes subhyllanus*) and long-horned grasshopper (*Ruspolia differens*). *Int J Trop Insect Sci* 41(2):1427–1433. <https://doi.org/10.1007/s42690-020-00337-y>
- Kinyuru JN, Ndung'u, N. W. (2020) Promoting edible insects in Kenya: historical, present and future perspectives towards establishment of a sustainable value chain. *J Insects Food Feed* 6(1):51–58. <https://doi.org/10.3920/JIFF2019.0016>
- Kinyuru JN, Kenji GM, Njoroge SM, Ayieko M (2010) Effect of processing methods on the in vitro protein digestibility and vitamin content of edible winged termite (*Macrotermes subhyllanus*) and grasshopper (*Ruspolia differens*). *Food Bioprocess Technol* 3(5):778–782. <https://doi.org/10.1007/s11947-009-0264-1>
- Kinyuru J, Kipkoech C, Imathiu S, Konyole S, Roos N (2021) Acceptability of cereal-cricket porridge compared to cereal and cereal-milk porridges among caregivers and nursery school children in Uasin Gishu, Kenya. *Int J Trop Insect Sci* 41(3):2007–2013. <https://doi.org/10.1007/s42690-020-00388-1>
- Kinyuru, JN, Kenji, G., & Njoroge, M. (2009). Process development, nutrition and sensory qualities of wheat buns enriched with edible termites (*Macrotermes subhyllanus*) from Lake Victoria region, Kenya. *Afr J Food, Agricult , Nutrit Dev* 9(8). <https://doi.org/10.4314/ajfand.v9i8.48411>
- Kinyuru John N, Nyangena D, Kamau E, Ndiritu A, Munji J, Kipkoech C, Weru J, Ndung'u N, & Mmari M (2018). The role of edible insects in diets and nutrition in east Africa. In *Edible Insects in Sustainable Food Systems* (pp. 93–108). Springer International Publishing. https://doi.org/10.1007/978-3-319-74011-9_6
- Kolobe SD, Manyelo TG, Malematja E, Sebola NA, Mabelebele M (2023) Fats and major fatty acids present in edible insects utilised as food and livestock feed. *Vet Anim Sci* 22:100312
- Konyole SO, Kinyuru JN, Owuor BO, Kenji GM, Onyango CA, Estambale BB, Friis H, Roos N, Owino VO (2012) Acceptability of Amaranth Grain-based Nutritious Complementary Foods with Dagaa Fish (*Rastrineobola argentea*) and Edible Termites (*Macrotermes subhyllanus*) Compared to Corn Soy Blend Plus among Young Children/Mothers Dyads in Western Kenya. *J Food Res* 1(3):111. <https://doi.org/10.5539/jfr.v1n3p111>
- Kouřimská L, Adámková A (2016) Nutritional and sensory quality of edible insects. *NFS J* 4:22–26. <https://doi.org/10.1016/J.NFS.2016.07.001>
- Kröncke N, Bösch V, Keil C, Grebenteuch S, Demtröder S, Thünnemann A, Kroh L, Haase H, & Benning R (2018). Comparison of suitable drying techniques on nutritional quality of mealworms (*Tenebrio molitor*). *Book of Abstracts*, 78.
- Kusia ES, Borgemeister C, Tanga CM, Ekesi S, Subramanian S (2021) Exploring community knowledge, perception and practices of entomophagy in Kenya. *Int J Trop Insect Sci* 41(3):2237–2246. <https://doi.org/10.1007/s42690-021-00469-9>
- Lamidi, R. O., Jiang, L., Pathare, P. B., Wang, Y. D., & Roskilly, A. P. (2019). Recent advances in sustainable drying of agricultural produce: A review. In *Applied Energy* (Vols. 233–234, pp. 367–385). <https://doi.org/10.1016/j.apenergy.2018.10.044>
- Lange KW, Nakamura Y (2021) Edible insects as future food: chances and challenges. *J Fut Foods* 1(1):38–46. <https://doi.org/10.1016/j.jfutfo.2021.10.001>
- Laroche M, Perreault V, Marciniak A, Gravel A, Chamberland J, Doyen A (2019) Comparison of conventional and sustainable lipid extraction methods for the production of oil and protein isolate from edible insect meal. *Foods* 8(11):572. <https://doi.org/10.3390/foods8110572>
- Li D, Sihamala O, Bhulaidok S, Shen L (2009) Changes in the organic compounds following sun drying of edible black ant (*Polyrhachis vicina* Roger). *Acta Aliment* 38(4):493–501
- Madibela OR, Seitiso TK, Thema TF, Letso M (2007) Effect of traditional processing methods on chemical composition and in vitro true dry matter digestibility of the Mophane worm (*Imbrasia belina*). *J Arid Environ* 68(3):492–500. <https://doi.org/10.1016/J.JARIDENV.2006.06.002>
- Maimba ZW, Kinyuru JN, Wanjala GW, Egonyu JP (2023) Inhibiting post-harvest perishability of edible beetle grubs (*Oryctes* spp) by blanching and pre-treatment with sodium metabisulphite and ascorbic acid. *LWT* 191:115659
- Maiyo NC, Khamis FM, Okoth MW, Abong GO, Subramanian S, Egonyu JP, Xavier C, Ekesi S, Omuse ER, Nakimbugwe D, Ssepuuya G, Ghemoh CJ, Tanga CM (2022) Nutritional Quality of Four Novel Porridge Products Blended with Edible Cricket (*Scaphispedus icipe*) Meal for Food. *Foods* 11:1047
- Manditsera FA, Lakemond CMM, Fogliano V, Zvidzai CJ, Luning PA (2018) Consumption patterns of edible insects in rural and urban areas of Zimbabwe: taste, nutritional value and availability are key elements for keeping the insect eating habit. *Food Security* 10:561–570
- Manditsera FA, Mubaiwa J, Matsungu TM, Chopera P, Bhatasara S, Kembo G, Mahlatini H, Ruzengwe FM, Matutu F, Grigor J, Fiore A, Macheka L (2022) Mopane worm value chain in Zimbabwe: Evidence on knowledge, practices, and processes in Gwanda District. *PLoS ONE* 17(12 December):1–17. <https://doi.org/10.1371/journal.pone.0278230>
- Mariod AA, Fadul H (2015) Extraction and characterization of gelatin from two edible Sudanese insects and its applications in ice cream making. *Food Sci Technol Int* 21(5):380–391. <https://doi.org/10.1177/1082013214541137>
- Mekuria SA, Kinyuru JN, Mokua BK, Tenagashaw MW (2021) Nutritional Quality and Safety of Complementary Foods Developed from Blends of Staple Grains and Honey Bee Larvae (*Apis mellifera*). *Int J Food Sci* 2021:5581585. <https://doi.org/10.1155/2021/5581585>
- Melgar-Lalanne G, Hernández-Álvarez AJ, Salinas-Castro A (2019) Edible Insects Processing: Traditional and Innovative Technologies. *Comprehen Rev Food Sci Food Safety* 18(4):1166–1191. <https://doi.org/10.1111/1541-4337.12463>
- Mmari MW, Kinyuru JN, Laswai HS, Okoth JK (2017) Traditions, beliefs and indigenous technologies in connection with the edible longhorn grasshopper *Ruspolia differens* (Serville 1838) in Tanzania. *J Ethnobiol Ethnomed* 13(1):1–11. <https://doi.org/10.1186/s13002-017-0191-6>
- Musundire R, Zvidzai CJ, Chidewe C, Ngadze RT, Macheka L, Manditsera FA, Mubaiwa J, Masheka A (2016) Nutritional and bioactive compounds composition of *Eulepida mashona*, an edible beetle in Zimbabwe. *J Insects Food Feed* 2(3):179–187
- Muthee MW, Khamis FM, Cheseto X, Tanga CM, Subramanian S, Egonyu JP (2024) Effect of cooking methods on nutritional value and microbial safety of edible rhinoceros beetle grubs (*Oryctes* sp). *Heliyon* 10(3):e25331. <https://doi.org/10.1016/j.heliyon.2024.e25331>
- Mutungi C, Irungu FG, Nduko J, Mutua F, Affognon H, Nakimbugwe D, Ekesi S, Fiaboe KKM (2019) Postharvest processes of edible insects in Africa: A review of processing methods, and the implications for nutrition, safety and new products development. *Crit Rev Food Sci Nutr* 59(2):276–298. <https://doi.org/10.1080/10408398.2017.1365330>
- Nakagaki BJ, Defoliart GR (1991) Comparison of Diets for Mass-Rearing *Acheta domestica* (Orthoptera: Gryllidae) as a Novelty

- Food, and Comparison of Food Conversion Efficiency with Values Reported for Livestock. *J Econ Entomol* 84(3):891–896. <https://doi.org/10.1093/jee/84.3.891>
- Ndiritu AK, Kinyuru JN, Kenji GM, Gichuhi PN (2017) Extraction technique influences the physico-chemical characteristics and functional properties of edible crickets (*Acheta domesticus*) protein concentrate. *J Food Measure Charac* 11(4):2013–2021. <https://doi.org/10.1007/s11694-017-9584-4>
- Ndiritu AK, Kinyuru JN, Gichuhi PN, Kenji GM (2019) Effects of NaCl and pH on the functional properties of edible crickets (*Acheta domesticus*) protein concentrate. *J Food Measurement Charac* 13(3):1788–1796. <https://doi.org/10.1007/s11694-019-00097-5>
- Ndiritu A, Kinyuru J, Onyango A, Kipkoech C (2023) Functional and microstructural characteristics of chitin extracted from field cricket, house cricket, and black soldier fly cocoons. *J Food Measure Charac* 17(6):5903–5912. <https://doi.org/10.1007/s11694-023-02086-1>
- Nganga J, Imathiu S, Fombong F, Ayieko M, VandenBroeck J, Kinyuru J (2019) Microbial quality of edible grasshoppers *Ruspolia differens* (Orthoptera: Tettigoniidae): From wild harvesting to fork in the Kagera Region Tanzania. *J Food Safety* 39(1):1–6. <https://doi.org/10.1111/jfs.12549>
- Niassy S, Affognon HD, Fiaboe KKM, Akutse KS, Tanga CM, Ekesi S (2016) Some key elements on entomophagy in Africa: Culture, gender and belief. *J Insects Food Feed* 2(3):139–144. <https://doi.org/10.3920/JIFF2015.0084>
- Nonaka K (1996) Ethnoentomology of the central Kalahari san. *Afr Study Monogr* 22:29–46 (<https://repository.kulib.kyoto-u.ac.jp/dspace/handle/2433/68378>)
- Nyangena DN, Mutungi C, Imathiu S, Kinyuru J, Affognon H, Ekesi S, Nakimbugwe D, Fiaboe KKM (2020a) Effects of Traditional Processing Techniques on the Nutritional and Microbiological Quality of Four East Africa. *Foods* 9:574
- Nyangena DN, Mutungi C, Imathiu S, Kinyuru J, Affognon H, Ekesi S, Nakimbugwe D, Fiaboe KKM (2020b) Effects of traditional processing techniques on the nutritional and microbiological quality of four edible insect species used for food and feed in East Africa. *Foods* 9(5):574
- Ochieng BO, Anyango JO, Nduko JM, Cheseto X, Mudalungu CM, Khamis FM, Ghemoh CJ, Egonyu PJ, Subramanian S, Nakimbugwe D (2022) Dynamics in nutrients, sterols and total flavonoid content during processing of the edible Long-Horned grasshopper (*Ruspolia differens* Serville) for food. *Food Chem* 383:132397
- Ochieng BO, Anyango JO, Khamis FM, Ekesi S, Egonyu JP, Subramanian S, Nduko JM, Nakimbugwe D, Cheseto X, Tanga CM (2023a) Nutritional characteristics, microbial loads and consumer acceptability of cookies enriched with insect (*Ruspolia differens*) meal. *LWT* 184:115012. <https://doi.org/10.1016/j.LWT.2023.115012>
- Ochieng BO, Anyango JO, Nduko JM, Mudalungu CM, Cheseto X, Tanga CM (2023b) Aroma characterization and consumer acceptance of four cookie products enriched with insect (*Ruspolia differens*) meal. *Sci Rep* 13(1):1–12. <https://doi.org/10.1038/s41598-023-38166-x>
- Ogidi CO, Ogunlade AO, Bodunde RS, Aladejana OM (2023) Evaluation of Nutrient Contents and Antioxidant Activity of Wheat Cookies Fortified with Mushroom (*Termitomyces robustus*) and Edible Insects. *J Cul Sci Technol* 00(00):1–19. <https://doi.org/10.1080/15428052.2023.2181253>
- Ojha S, Bußler S, Psarianos M, Rossi G, Schlüter OK (2021) Edible insect processing pathways and implementation of emerging technologies. *J Insects Food Feed* 7(5):877–900. <https://doi.org/10.3920/JIFF2020.0121>
- Oladiran DA, Emmambux NM (2022) Locally Available African Complementary Foods: Nutritional Limitations and Processing Technologies to Improve Nutritional Quality—A Review. *Food Rev Intl* 38(5):1033–1063. <https://doi.org/10.1080/87559129.2020.1762640>
- Omuse ER, Tonnang HEZ, Yusuf AA, Machezano H, Egonyu JP, Kimathi E, Mohamed SF, Kassie M, Subramanian S, Onditi J, Mwangi S, Ekesi S, Niassy S (2024) The global atlas of edible insects: analysis of diversity and commonality contributing to food systems and sustainability. *Sci Rep* 14(1):1–17. <https://doi.org/10.1038/s41598-024-55603-7>
- Oonincx D, Finke MD (2021) Nutritional value of insects and ways to manipulate their composition. *J Insects Food Feed* 7(5):639–659
- Oonincx DGAB, van Itterbeeck J, Heetkamp MJW, van den Brand H, van Loon JJA, van Huis A (2010) An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLoS ONE* 5(12):e14445. <https://doi.org/10.1371/JOURNAL.PONE.0014445>
- Oonincx DGAB, Van Broekhoven S, Van Huis A, Van Loon JJA (2015) Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS ONE* 10(12):e0144601. <https://doi.org/10.1371/JOURNAL.PONE.0144601>
- Opstvedt J, Nygård E, Samuelsen TA, Venturini G, Luzzana U, Mundheim H (2003) Effect on protein digestibility of different processing conditions in the production of fish meal and fish feed. *J Sci Food Agric* 83(8):775–782
- Otero P, Gutierrez-Docio A, Del Hierro JN, Reglero G, Martin D (2020) Extracts from the edible insects *Acheta domesticus* and *Tenebrio molitor* with improved fatty acid profile due to ultrasound assisted or pressurized liquid extraction. *Food Chem* 314:126200. <https://doi.org/10.1016/j.foodchem.2020.126200>
- Ouma FO, Muriithi AN, Anyango JO (2022) Nutritional composition and sensory Properties of wheat muffins enriched with *Gonimbrasia zambesina*, walker caterpillar flour. *Int J Trop Insect Sci* 42(4):3097–3105. <https://doi.org/10.1007/s42690-022-00848-w>
- Payne CLR, Scarborough P, Rayner M, 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(3):285–291. <https://doi.org/10.1038/ejcn.2015.149>
- Raheem D, Carrascosa C, Oluwale OB, Nieuwland M, Saraiva A, Millán R, Raposo A (2019) Traditional consumption of and rearing edible insects in Africa, Asia and Europe. *Crit Rev Food Sci Nutr* 59(14):2169–2188. <https://doi.org/10.1080/10408398.2018.1440191>
- Raubenheimer D, Rothman JM (2013) Nutritional ecology of entomophagy in humans and other primates. *Ann Rev Entomol* 58(September 2012):141–160. <https://doi.org/10.1146/annurev-ento-120710-100713>
- Rumpold BA, Schlüter OK (2013) Nutritional composition and safety aspects of edible insects. *Mol Nutr Food Res* 57(5):802–823. <https://doi.org/10.1002/mnfr.201200735>
- Séré A, Bougma A, Bazié BSR, Nikiéma PA, Gnankiné O, Bassolé IHN (2022) Nutritional and Functional Properties of Defatted Flour, Protein Concentrates, and Isolates of *Brachytrupes membranaceus* (Orthoptera: Gryllidae) (Drury: 1773) and *Macrotermes subhyalinus* (Isoptera: Blattodea) (Rambur: 1842) from Burkina Faso. *Insects* 13(9):1–12. <https://doi.org/10.3390/insects13090764>
- Ssepuuya G, Nakimbugwe D, De Winne A, Smets R, Claes J, Van Der Borgh M (2020) Effect of heat processing on the nutrient composition, colour, and volatile odour compounds of the long-horned grasshopper *Ruspolia differens* serville. *Food Res Int* 129:108831. <https://doi.org/10.1016/j.foodres.2019.108831>
- Tao J, Li YO (2018) Edible insects as a means to address global malnutrition and food insecurity issues. *Food Qual Safety* 2(1):17–26. <https://doi.org/10.1093/fqsafef/fyy001>

- Tiencheu B, Womeni HM, Linder M, Mbiapo FT, Villeneuve P, Fanni J, Parmentier M (2013) Changes of lipids in insect (*Rhynchophorus phoenicis*) during cooking and storage. *Eur J Lipid Sci Technol* 115(2):186–195. <https://doi.org/10.1002/ejlt.201200284>
- Tzompa-Sosa DA, Yi L, van Valenberg HJF, van Boekel MAJS, Lakemond CMM (2014) Insect lipid profile: aqueous versus organic solvent-based extraction methods. *Food Res Int* 62:1087–1094. <https://doi.org/10.1016/j.foodres.2014.05.052>
- van Huis A (2020) Insects as food and feed, a new emerging agricultural sector: A review. *J Insects Food Feed* 6(1):27–44. <https://doi.org/10.3920/JIFF2019.0017>
- Van Huis A, Rumpold BA, Van der Fels-Klerx HJ, Tomberlin JK (2021) Advancing edible insects as food and feed in a circular economy. *J Insects Food Feed* 7(5):935–948
- van Huis Arnold, Oonincx DGAB (2017). The environmental sustainability of insects as food and feed. A review. *Agro Sustain Dev* 37(5). <https://doi.org/10.1007/s13593-017-0452-8>
- Van Huis A (2003). Insects as food in Sub-Saharan Africa. In *Insect Science and its Application* (Vol. 23, Issue 3, pp. 163–185). Cambridge University Press. <https://doi.org/10.1017/s1742758400023572>
- Verneau F, Amato M, La Barbera F (2021) Edible insects and global food security. *Insects* 12(5):10–12. <https://doi.org/10.3390/insects12050472>
- Wanjala MN, Orinda M, Nyongesah JM, Tanga CM, Subramanian S, Kassie M, Egonny JP (2023) Socio-cultural practices on the use of beetle grubs as food and feed in western Kenya. *Sci Rep* 13(1):7805
- Wegier A, Alavez V, Pérez-López J, Calzada L, Cerritos R (2018) Beef or grasshopper hamburgers: The ecological implications of choosing one over the other. *Basic Appl Ecol* 26:89–100. <https://doi.org/10.1016/j.baae.2017.09.004>
- Weru J, Chege P, Kinyuru J (2021) Nutritional potential of edible insects: a systematic review of published data. *Int J Trop Insect Sci* 41(3):2015–2037. <https://doi.org/10.1007/s42690-021-00464-0>
- Weru J, Chege P, Wanjaya A, Kinyuru J (2022) Comparison of healthfulness of conventional meats and edible insects in Sub-Saharan Africa using three nutrient profiling models. *Bull Nat Res Centre* 46(1):43. <https://doi.org/10.1186/s42269-022-00726-y>

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