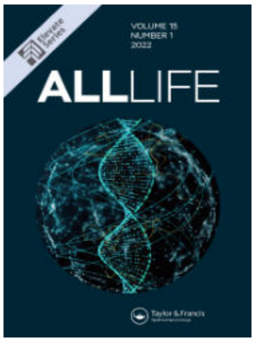

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REVIEW

Scope and present status of rearing edible insects for animal feeding in Africa

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ABSTRACT
Edible insects have sparked more research interest as a cheap alternative protein source to replace soya bean and fish meal in animal diets due to their good nutritional value. In general, information on various insects has been widely researched globally. In Africa, the available literature focused more on traditional harvesting of edible insects for use as food and feed. The collection of insects in the wild is considered unsustainable since it leads to overharvesting, endangering and extinction of insects, consequently destabilising the ecosystem. This review discusses and compares the recent findings on the nutritional composition of common African edible insects with nutrient requirements of livestock. This is followed by compiled data of their proximate composition, amino acid, mineral, fatty acids and vitamin contents as derived from the literature. The review also describes insect availability, quantity, quality and production systems used to rear insects for animal feeding in Africa. Insect market demand, benefits and challenges of producing insects as livestock feed are summarised. Lastly, the legislations and regulations imposed on insect harvesting and rearing are thoroughly discussed. The current review findings will provide valuable answers to the present status of sustainable insect production in Africa to meet animal nutrient requirements.

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Animal diets; edible insects; Africa; farming systems; sustainability

Introduction

The global food crisis continues to escalate, especially in developing countries due to economic crisis, population growth and climate change (Malatsi, 2019; Anankware et al. 2021). It is estimated that about 21% of people in Africa suffer from undernutrition; hence there is a need to urgently address food insecurity (Adegboye et al. 2021). Edible insects have been identified as a possible alternative protein source for livestock, especially poultry and fish species (Tilami et al. 2020; Hermans et al. 2021; Adli 2021). In African tradition, edible insects are harvested as seasonal food for human consumption to alleviate undernutrition and address food insecurity (Hlongwane et al. 2021; Salter 2019; Kim et al. 2019; van Huis 2020; Magara et al. 2021; Abdullahi et al. 2021). For instance, countries in East Africa such as Kenya, Uganda and Madagascar prefer to consume *Schistocerca gregaria*, *Ruspolia differens*, *Macrotermes* spp., *Macrotermes bellicosus* and *Rhynchophorus phoenicis* larvae (Tanga et al. 2021). West African countries including Nigeria, Ghana, Senegal and Ivory Coast prefer *Rhynchophorus phoenicis* larvae, *Cirina butyrospermi* larvae and *Macrotermes bellicosus* (Anankware et al. 2021). Southern Africans, namely South Africa, Zimbabwe, Namibia and Zambia, eat *Gonimbrasia belina*, *Macrotermes subhyalinus*, *Schistocerca gregaria* and *Encosternum delegorguei.* Central Africa such as Cameroon and DRC Congo prefers consuming *Rhynchophorus phoenic* and *Cirina forda* (Tanga et al. 2021). The sustainable insect production is in line with 8 (1, 2, 3, 6, 7, 8, 9 and 12) of 17 Sustainable Development Goals (SDGs) implemented by the United Nations which aims at food sustainability and total eradication of poverty by 2030 (Kewuyemi et al. 2020; Sithole et al. 2021; Tanga et al. 2021). Moreover, the objectives of the second goal (SDG2) are committed to promote sustainable agriculture and improved nutrition for all individuals (Hendriks et al. 2018). The 2030 SDGs targets are also discussed in Africa's

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Agenda 2063 'The Africa We Want', which also targets zero hunger and sustainable development (Hendriks et al. 2018; Sithole et al. 2021). Moreover, 'The Africa We Want' defines 20 goals and 256 targets outlined to uplift and improve Africa in becoming a better continent. It is committed to sustainable consumption, production and management of ecosystems (Sithole et al. 2021). Hence, drastic efforts on discovering high-quality, cost-effective feeds that are biofriendly and available on a large scale (insect farming) with good health benefits and sufficient nutrients that meet daily nutritional requirements of livestock will aid in addressing SDGs targets on food security (Kewuyemi et al. 2020; Dürr and Ratompoarison 2021).

Nevertheless, the potential of edible insects as an animal feed source due to their high nutritive value is well documented and acknowledged worldwide (Nyangena et al. 2020). In Africa, there are about 470–500 recorded edible insect species found in abundance mainly in Central and Southern African countries (Kelemu et al. 2015; Abdullahi et al. 2021). Nonetheless, they occur seasonally at different emerging periods throughout the year and could be utilised efficiently in animal diets depending on insect type, developmental stage, quantity and quality, animal nutrient requirement and safe consumption. Examples of insects include caterpillars, locusts, termites and stinkbugs belonging to the order of Lepidoptera, Orthoptera, Isoptera and Hemiptera respectively (Kewuyemi et al. 2020). Moreover, their orderly morphological life stages include egg, nymph, pupae or adult stage (FAO 2010). Although insect farming is already implemented in African countries such as Kenya (Nyangena et al. 2020), there is lack of information on the present status of producing edible insects as animal feed source in terms of their quantity and quality in Africa.

This review assesses the present status of farming edible insects for feeding animals in Africa with an overview on the nutritional value, quantity, production systems used and legislations imposed on the productivity of edible insects as animal feeds. This will give clarity on the sustainability of insect farming in Africa based on looking at the quantity and efficiency of production systems adopted in the continent.

Nutritive value of African edible insects versus nutrient requirement of animals

Proximate composition

Edible insects have been widely reported to be rich in protein, lipids, vitamins and minerals (Rumpold and Schluter 2013; Mwimanzi and Musuka 2016; Musundire et al. 2016; Nogales-Merida et al. 2019; Mousavi et al. 2020; Mulazzani et al. 2021; Tanga et al. 2021). The nutritional characteristics of insects play an important role in measuring the quality of insect meals to potentially become a protein alternative to traditional protein ingredients (Freccia et al. 2020). It has been reported that protein content found in edible insects either at fresh or dry weight was observed to be superior to plant protein sources, including soybeans (Schluter et al. 2017; Kim et al. 2019). Furthermore, nutritional value of most edible insects has been reported to be comparable or superior to that of conventional food sources such as beef, pork, chicken and eggs (Kewuyemi et al. 2020; Mlcek et al. 2014; Tang et al. 2019; Akpalu et al. 2009; Egan et al. 2014; Hlongwane et al. 2021 Bauserman et al. 2015; Kuntadi et al. 2018; Lange and Nakamura 2021), as well as plant protein sources, including soybeans (Kim et al. 2019). The proximate nutrient composition of 21 common African edible insects on a dry matter basis, along with nutrient requirements for livestock is shown in Table 1. All edible insects presented in the table have enormous protein and energy above the recommended levels. However, insects under Orthoptera order including locusts and crickets have the highest protein content, between 46.30% and –76.00% whereas the orders Hemiptera (stinkbugs) and Isoptera (termites) have the highest energy level, between 625.82–2599.00 kcal and 496.50–696.10 kcal, respectively. Hence, these orders could potentially be a good source of protein and energy since they meet nutrient requirement livestock, specifically for poultry, fish and beef cattle. However, it has been reported that the nutrient composition including protein from insects can be influenced by the type of diet they consume or substrate, thus their nutritional value could successfully be manipulated through feeding (Wessels et al. 2007; Oonincx 2021; Meyer-Rochow et al. 2021). Hence, African edible insects could provide sufficient amounts of protein and energy content required by animals daily.

Table 1. Proximate nutrient composition of common African edible insects (on a dry matter basis)

		Compositions (%)								
Insect species	Stage	Protein	Fat	Fibre	Dry matter	Carbohydrate	Moisture	Ash	Energy (kcal per 100 g)	References
Caterpillars (Lepidoptera)										
Gonimbrasia belina	L	55.30-65.80	15.16-23.38	-	87.30	8.20-10.98	12.70	8.30-12.50	250.00-352.00	Egan 2013; Tang et al. 2019; Hlongwane et al. 2021; Govorushko 2019
Hemijana variegata	L	52.42	19.33	8.32	-	9.49	5.87	5.23	552.00	Egan et al. 2014; Hlongwane et al. 2021
Beetles (Coleoptera)										
Tenebrio molitor	L	38.30-52.35	24.70-43.08	1.97-20.22	-	2.20-26.25	2.80	2.36-4.10	444.00-577.40	Rumpold and Schluter 2013; Zielinska et al. 2017; Kim et al. 2019: Kuntadi et al. 2018; Tang et al. 2019; Meyer-Rochow et al. 2021
Rhynchophorus phoenicis	L	28.40-45.44	21.10-69.78	2.58-25.14	-	6.59	2.70-26.00	1.43-6.06	478.87-584.68	Rumpold and Schluter 2013; Dobermann et al. 2017; Tang et al. 2019; Kewuyemi et al. 2020; Hlongwane et al. 2021
Sternocera orissa	A	63.00	9.83	-	-	20.62	3.74	2.80	426.00	Egan 2013
Locusts (Orthoptera)										
Nomadacris succincta		27.60	4.70							Kuntadi et al. 2018
Schistocerca gregaria		46.30-76.00	12.97-32.30	2.53-11.00	82.39-93.56	0.02-9.90	6.44-17.61	2.70-6.70	4270.00-527.49	Dobermann et al. 2017; Khalil 2018; Zielinska et al. 2017; Egonyu et al., 2021; Fombong et al. 2021
Locusta migratoria	A	54.16	30.52	9.19	77.77	-	22.23	3.08	179.00-512.34	Govorushko 2019; Fombong et al. 2021
Stinkbugs (Hemiptera)										
Encosternum delegorguei	A	35.20-43.30	45.00-50.50	5.30	95.10	7.63	4.90	1.70	625.82-2599.00	Teffo 2007; Magara et al. 2021; Kewuyemi et al. 2020; Musundire et al. 2016; Hlongwane et al. 2021
Euschistus egglestoni	A	35.00-46.00	45.00	19.00	-	-	-	1.00	548.00	Rumpold and Schluter 2013; Tang et al. 2019
Termites (Isoptera)										
Macrotermes bellicosus	A	22.44-40.70	26.30-48.00	1.69-6.21	96.15	3.48-7.42	3.85-22.79	1.18-11.26	496.50-696.10	Rumpold and Schluter 2013; Paul et al. 2020; Meyer-Rochow et al. 2021; Akullo et al. 2018; Tang et al. 2019
Macrotermes nigeriensis	A	35.90-37.50	34.23-50.90	5.50-6.30	-	20.74	3.00-5.80	3.0-5.80	-	Fombong and Kinyuru 2018; Meyer-Rochow et al. 2021; Hlongwane et al. 2021
Macrotermes natalensis	A	20.94-65.62	21.40-22.50	2.20-7.85	-	42.80	2.98-3.00	1.90-4.10	467.00	Egan 2013; Rumpold and Schluter 2013; Fombong and Kinyuru 2018; Hlongwane et al. 2021
Macrotermes subhyalinus	A	38.42-39.34	44.82-47.00	6.20-6.37	-	1.86-7.98	0.94-6.50	4.7—6.56	535.00-612.00	Fombong and Kinyuru 2018; Govorushko 2019; Meyer-Rochow et al. 2021
Crickets (Orthoptera)										
Gryllus assimilis	A	56.00-71.04	7.00-32.00	7.00-8.28	-	12.46	3.50	6.00	397.00	Tang et al. 2019; Kewuyemi et al. 2020; Meyer-Rochow et al. 2021
Gryllus bimaculatus	A	58.30-65.34	11.9-20.74	5.80-9.50	73.66	8.16	26.34	4.11-9.70	120.00-469.91	Govorushko 2019; Kewuyemi et al. 2020; Meyer-Rochow et al. 2021; Fombong et al. 2021
Acheta domesticus	A	62.00-62.60	12.20-22.96	8.00	-	-	-	5.0	455.19	Dobermann et al. 2017; Tang et al. 2019; Meyer-Rochow et al. 2021
Flies (Diptera)										
Hermetia illucens	L	39.00-49.00	18.03-32.60	12.40	92.24	-	-	14.60-17.71	-	Tang et al. 2019; Anankware et al. 2021; Meyer-Rochow et al. 2021
Musca domestica	L	54.00-63.99	11.49-24.31	-	88.45	-	-	5.16-9.84	552.40	Rumpold and Schluter 2013; Tang et al. 2019; Anankware et al. 2021
Ants (Hymenoptera)										
Carebara vidua	A	40.80-42.50	38.20-47.50	6.90-9.10	-	-	3.90	1.60	-	Rumpold and Schluter 2013; Hlongwane et al. 2021
Animal nutrient requirements										
Broiler chickens (%)		18.00-23.00	-	-	-	-	-	-	419–432	NRC 1994
Egg layers		15.00-18.00	-	-	-	-	-	-	350.00-400.00	NRC 1994
Turkey		14.00-28.00	-	-	-	-	-	-	-	NRC 1994
Fish		30–52	-	-	-	-	-	-	290.00-410.00	NRC 1993
Beef cattle (%)		7.00	-	-	-	-	-	-	390.00-610.00	Lalman and Richards 2017

L = larvae; A = adult; '-' = Not reported

Essential amino acids composition

Nogales-Merida et al. (2019) reported that insect meals can be a good source of essential amino acids, more especially threonine and methionine (Straub et al. 2019) as they are found in large quantities compared to other protein meals. The amino acid composition of common African edible insects on a dry matter basis, along with amino acid requirements for livestock are shown in Table 2. Almost all the insects have sufficient to high essential amino acids that meet the requirements for poultry species. Hence, their good amino acid profile shows that they can be a possible protein source of high quality in livestock diets (Hermans et al. 2021). Additionally, the essential amino acid content found in insect meals is reported to be much higher than that of traditional feedstuffs (Henry et al. 2015; Adli 2021; Hlongwane et al. 2021; Elahi et al. 2022). Although the amount of methionine in edible insects is slightly low compared to other amino acids, it could be supplemented in diets to improve health and proper cell functioning of the animal (Selaledi et al. 2020). However, species *Tenebrio molitor* (caterpillar) and *Gryllus bimaculatus* (cricket) contained highest levels of amino acids including lysine and methionine, which ranges between 2.49–11.40 g/100 g and 0.27–4.00 g/100 g respectively, compared to other reported species. Hence, the good amino acid profile denotes that they could potentially be utilised as a protein source of high quality (Hermans et al. 2021).

Mineral composition

They have been reported to contain high-level essential minerals including trace elements (Kim et al. 2019). Table 3 shows the mineral composition of insects and the recommended mineral daily intakes for poultry, beef cattle and fish. Most edible insects have insufficient amounts of calcium recommended for laying chickens and fish; hence, calcium supplementation is necessary when edible insects are included in their diets. Adli (2021) reported that insect meal contains low calcium and phosphorus content compared to fish meal; however, insect meal calcium level depends on the rearing method exposed to. Furthermore, other minerals are sufficient, and some are above the recommended levels to meet the daily requirements for livestock. The orders Orthoptera (locust and cricket) and Diptera (flies) contain higher calcium content, ranging between 27.10–240.17 mg/100 g and 934.00–2010.00 mg/100 g respectively. Insect meals have high levels of potassium, magnesium, phosphorus, zinc and iron (Mwimanzi and Musuka 2016; Ramos-Elorduy et al. 2012; Rumpold and Schluter 2013; Kuntadi et al. 2018; Khalil 2018; Kim et al. 2019; Elahi et al. 2022). Hence, they could be safely included in feed.

Vitamin composition

The vitamin composition of edible insects along with vitamin requirements by animals are shown in Table 4. Although the data on some of the vitamins present in insects below were not reported, the orders Lepidoptera (*Rhynchophorus phoenicis*), Isoptera (*Macrotermes bellicosus*) and Orthoptera (*Acheta* spp.) contain high vitamin A that ranges between 11.25 mg/100 g, 2.9–11.37 mg/100 g and 24.33–67.00 mg/100 g, respectively. Most insects also have considerable amounts of vitamin B12 and vitamin D which meet the vitamin requirement by poultry species such as broilers, layers and turkey. However, edible insects lack vitamin B2 and B3, hence, the inclusion of edible insects will require supplementation of the above-mentioned minerals.

Common edible insects produced in Africa

Traditionally, Africa is popularly known to harvest edible insects seasonally in the wild, rather than produce them in farms and laboratories (Dzerefos et al. 2013; FAO 2013; Orinda et al. 2018; Tanga et al. 2021). Hence, only crickets and black soldier flies are reported to be farmed under few production systems for utilising as animal feed (Orinda et al. 2018). These insects are mainly known to occupy different habitats including grassland, bushes, forests, trees, marshes, beaches, caves, underground and in buildings (Magara et al. 2021). According to Rapatsa and Moyo (2017) and Mnisi et al. (2022), their mass production, breeding and processing could be both profitable and sustainable. However, they require favourable climatic conditions for efficient productivity (Nischalke et al. 2020). Therefore, factors such as the type of insect species, stage of development, insect population, rearing medium, type of diet for insects, eating habits of animals-fed insects, environmental conditions, environmental contamination and insect

Table 2. Essential amino acid composition of common African edible insects (on a dry matter basis).

		Compositions (g/100 g)								
Insect species	Stage	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine	References
Caterpillars (Lepidoptera)										
Gonimbrasia belina	L	1.30	1.83	1.46	0.41	1.35	0.60	1.48	1.12	Orkusz 2021
Tenebrio molitor	L	4.00-8.35	6.90-14.00	4.90-10.70	1.20-4.00	3.20-6.54	3.60-7.70	1.00-2.16	5.90-12.80	Tang et al. 2019; Orkusz 2021
Rhynchophorus phoenicis	L	7.80	5.90	6.40	1.20	3.30	1.40	0.50	5.50	Tang et al. 2019
Locusts (Orthoptera)										
Schistocerca gregaria	A	2.82-4.63	7.77-8.23	3.51-4.57	0.82-0.95	1.87-3.63	3.55-3.95	0.82	5.66-6.87	Zielinska et al. 2017; Fombong et al. 2021
Locusta migratoria	A	4.62	8.46	4.78	0.39	3.49	3.96	0.97	7.21	Fombong et al. 2021
Stinkbugs (Hemiptera)										
Encosternum delegorguei	A	0.83-3.18	1.05-7.11	0.85-0.88	0.40-1.08	0.81-2.10	0.42-0.82	0.16-3.39	0.97-1.32	Kewuyemi et al. 2020; Musundire et al. 2016
Euschistus egglestoni	A	4.40	7.00	3.00	2.80	3.30	4.80	0.60	6.10	Tang et al. 2019
Termites (Isoptera)										
Macrotermes bellicosus	A	5.10	7.80	5.40	0.80	4.40	2.80	1.40	7.30	Tang et al. 2019
Macrotermes subhyalinus	A	3.55	-	6.40	1.50	10.65	3.80	-	-	Fombong and Kinyuru 2018
Crickets (Orthoptera)										
Gryllus assimilis	A	2.12-3.40	6.60-7.74	5.00-7.90	0.63-1.20	0.72-2.90	3.30-3.55	0.70-0.95	4.62-5.30	Tang et al. 2019; Magara et al. 2021
Gryllus bimaculatus	A	2.16-9.20	3.97-16.50	2.42-11.40	0.27-3.50	1.83-7.40	2.00-8.10	2.20	3.20-13.60	Magara et al. 2021; Fombong et al. 2021; Orkusz 2021
Acheta domesticus	A	2.60-4.45	4.50-9.75	3.50-5.40	0.90-1.40	1.40-3.00	2.20-3.60	0.40-0.55	1.07-3.70	Tang et al. 2019; Magara et al. 2021; Oonincx and Finke 2021
Flies (Diptera)										
Hermetia illucens	L	4.00-4.33	6.60-6.96	5.60-5.91	1.40-1.88	3.80-4.15	3.60-3.90	1.10-1.51	5.60-6.38	Tang et al. 2019; Oonincx and Finke 2021
Musca domestica	L	3.20	5.70	6.90	2.20	5.00	3.30	3.20	4.40	Tang et al. 2019
Daily requirement in animals										
Broiler chickens		0.62-0.80	0.93-1.68	0.55-1.18	0.29-0.57	0.56-0.72	0.45-0.85	0.14-0.23	0.69-0.90	NRC 1994
Egg layers		0.48-0.65	0.82	0.62-0.69	0.30	0.47	0.40-0.47	0.16-0.24	0.64-0.70	NRC 1994
Turkey		0.31-1.10	0.53-1.96	0.32-1.68	0.15-0.60	0.30-1.05	0.32-1.14	0.06-0.37	0.40-1.38	NRC 1994
Fish		0.90	1.30-1.60	2.00-2.20	1.20-1.60	2.10-2.50	0.90-1.50	0.20-0.30	1.30-1.40	NRC 1993

L = larvae; A = adult; '-' = Not reported.

Table 3. Mineral composition of common African edible insects (dry weight).

		Compositions (mg/100 g DM)							
Insect species	Stage	Calcium	Phosphorus	Magnesium	Potassium	Sodium	Iron	Zinc	References
Caterpillars (Lepidoptera)									
Gonimbrasia belina	L	0.80–17.00	14.80-543.00	56.00–160.00	1.20–36.30	26.90–33.50	11.80–54.50	1.90–16.60	Payne et al. 2016; Hlongwane et al. 2021 Kewuyemi et al. 2020; Verspoor et al. 2020; Mnisi et al. 2022
Tenebrio molitor	L	27.61-47.18	264-748.03	62.00-304.00	337.00-895.01	53.70-140.94	2.47-6.00	4.33-14.40	Zielinska et al. 2017; Kim et al. 2019; Kuntadi et al. 2018; Tang et al. 2019; Orkusz 2021; Verspoor et al. 2020
Rhynchophorus phoenicis	L	54.10-131.05	352.00-518.50	82.70-131.80	546.78-1617.00	48.40-56.18	14.70-22.75	10.15-26.50	Dobermann et al. 2017; Tang et al. 2019; Kewuyemi et al. 2020; Hlongwane et al. 2021
Locusts (Orthoptera)									
Nomadacris spp.	A	27.10	-	-	-	-	3.15	-	Kuntadi et al. 2018
Schistocerca gregaria	A	70.00-208.40	171.00	34.60-82.00	101.30-749.00	27.60-281.40	2.90-8.38	3.70-18.60	Zielinska et al. 2017; Khalil 2018; Egonyu et al. 2021
Locusta migratoria	A	-	-	85.00	-	-	9.20	25.00	Verspoor et al. 2020
Stinkbugs (Hemiptera)									
Encosternum delegorguei	A	91.00	575.00	109.00	275.00	55.30	20.20	46.00	Teffo 2007; Magara et al. 2021; Kewuyemi et al. 2020; Musundire et al. 2016; Mabelebele et al. 2022
Euschistus egglestoni	A	204.00	-	1910.00	108.00	397.00	57.00	59.00	Tang et al. 2019; Mabelebele et al. 2022
Termites (Isoptera)									
Macrotermes bellicosus	A	20.80-63.6	136.00-385.15	185.50	229.00	396.10	27.00-116.00	7.65-10.80	Fombong and Kinyuru 2018; Tang et al. 2019; Kewuyemi et al. 2020; Hlongwane et al. 2021; Meyer-Rochow et al. 2021
Macrotermes nigeriensis	A	0.10	1.49	6.10	336.00	112.00	0.96	0.10	Fombong and Kinyuru 2018; Tang et al. 2019
Macrotermes natalensis	A	18.00	114.00	0.30	-	-	29.00	-	Fombong and Kinyuru 2018;Hlongwane et al. 2021
Macrotermes subhyalinus	A	22.00-58.70	182.30	42.63-104.80	259.60	123.60	11.52-53.3	8.10-10.23	Kinyuru, 2009; Meyer-Rochow et al. 2021; Verspoor et al. 2020
Crickets (Orthoptera)									
Gryllus assimilis	A	45.30	0.80	2.19-8.92	367.13	0.42-0.99	0.15-2.78	0.24-1.42	Kewuyemi et al. 2020; Magara et al. 2021
Gryllus bimaculatus	A	105.14-240.17	702.02-1169.60	72.94-143.65	321.71-1079.90	88.84-452.99	9.50-9.66	14.39-22.43	Orkusz 2021; Magara et al. 2021; Mabelebele et al. 2022
Acheta domesticus	A	99.6-171.07	832.90-957.79	55.10-109.42	126.62-1126.62	167.00-435.06	5.46-9.20	6.71-26.60	Dobermann et al. 2017; Orkusz 2021; Tang et al. 2019; Magara et al. 2021; Verspoor et al. 2020
Flies (Diptera)									
Hermetia illucens	L	934.00	356.00	174.00	453.00	88.70	6.66	5.62	Tang et al. 2019
Musca domestica	L	2010.00	1320.00	-	-	660.00	60.40	23.70	Tang et al. 2019
Ants (Hymenoptera)									
Carebara vidua	A	22.30	106.00	10.40	-	-	10.40-10.70	5.70	Hlongwane et al. 2021
Recommended daily intakes									
Broiler chickens		8.00-10.00	0.30-0.45	600.00	3.00	1.30-2.00	80.00	40.00	NRC 1994
Egg layers		2710.00-3250.00	150.00-250.00	355.00-900.00	1.30	130.00-150.00	45.00-55.00	28.00-54.00	NRC 1994
Turkey		6.00-17.00	2.10-8.00	475.00	3.50-8.00	1.20-2.50	-	41–70	NRC 1994
Cattle		1.60-3.80	1.20-2.00	1.00-4.00	6.00-30.00	0.60-1.00	-	-	Lalman and Richards 2017
Fish		1300.00-1500.00	-	240–770	2000.00-8000.00	-	30.00-330.00	15.00-200.00	Antony Jesu Prabhu et al. 2016

L = larvae; A = adult; '-' = Not reported.

Table 4. Vitamin composition of common African edible insects (on a dry matter basis).

		Compositions (mg/100 g)										
Insect species	Stage	Vit A	Vit B1	Vit B2	Vit B3	Vit B5	Vit B12	Vit C	Vit D	Vit E	Vit K	References
Caterpillars (Lepidoptera)												
Tenebrio molitor	L	0.02-0.03	0.18	0.81-1.21	4.07-4.65	-	0.47 (ug)	1.80-9.90	-	1.31-1.90	-	Orkusz 2021
Hemijana variegata	L	0.02	0.01	0.65	-	-	-	14.15	-	0.64	-	Egan 2013
Rhynchophorus phoenicis	L	11.25	-	2.20	-	-	-	4.3	-	-	-	Dobermann et al. 2017; Hlongwane et al. 2021
Locusts (Orthoptera)												
Schistocerca gregaria	A	-	-	-	-	-	0.22	-	-	-	-	Fombong et al. 2021
Locusta migratoria	A	-	-	-	-	-	1.10	-	-	-	-	Fombong et al. 2021
Stinkbugs (Hemiptera)												
Encosternum delegorguei	A	0.23	0.63	0.86	-	-	-	-	-	2170.00	-	Kewuyemi et al. 2020; Hlongwane et al. 2021
Termites (Isoptera)												
Macrotermes bellicosus	A	2.90-11.37	0.87	0.32–2.00	1.59	-	-	3.40-3.58	2.22	3600.00	–	Kewuyemi et al. 2020; Hlongwane et al. 2021
Macrotermes nigeriensis	A	0.35	0.67	1.56	2.74	–	–	17.76				Fombong and Kinyuru 2018
Macrotermes natalensis	A	2.56	–	1.54	–	–	–	3.01	–	–	–	Fombong and Kinyuru 2018; Hlongwane et al. 2021
Macrotermes subhyalinus	A	–	0.131	1.14	4.59	–	–	–	–	–	–	Fombong and Kinyuru 2018
Crickets (Orthoptera)												
Gryllus assimilis	A	2.90	–	0.23	–	–	10.00	1.01	–	330.00	40.00	Magara et al. 2021; Kewuyemi et al. 2020
Gryllus bimaculatus	A	–	0.36	1.91	3.10	–	1.35		–	–	–	Fombong et al. 2021; Orkusz 2021
Acheta spp.	A	24.33–67.00	0.04	3.14–3.41	3.84	2.30	0.01	3.00	17.15	1.32	151.90	Magara et al. 2021; Dobermann et al. 2017; Orkusz 2021
Vitamin requirement by animals												
Broiler chickens		0.90–2.20	–	2.30–5.10	20.00–37.00	5.00–14.00	0.01	–	0.21–0.40	0.01–0.05	0.37–0.59	NRC 1994
Egg layers		2.75–3.52	–	2.50–3.60	9.00–21.00	1.90–8.90	0.50–2.00 (ug)	–	0.15–0.25	0.01	> 1.00	NRC 1994
Turkey		2.00–5.28	–	2.70–4.00	21.00–71.50	8.6–10.5	0.002–0.010	–	0.30–1.10	0.01–0.28	1.76	NRC 1994

L = larvae; A = adult; '–' = Not reported; Vit = Vitamin.

processing methods must be considered, as they determine their nutrient quality and quantity (Sanchez-Muros et al. 2014; van Huis and Oonincx 2017; Alfaro et al. 2019; DiGiacomo and Leury 2019; Abdullahi et al. 2021; Elahi et al. 2022).

Crickets

Crickets are known to adapt and thrive well in different rearing conditions, mainly organic materials such as forage diets and feed residues (Makkar et al. 2014; Khan 2018; Orinda et al. 2018). Common crickets produced under African rearing systems for animal feed include *Gryllus bimaculatus* and *Acheta domesticus*, which take about 6–12 weeks to reach maturity (Magara et al. 2021; Orinda et al. 2018; Biancarosa et al. 2019). Although slow growth and cannibalism are some of the factors that negatively affect the sustainable mass production of cricket species (Nischalke et al. 2020), insect farms in Africa have been reported to produce about 85 kg of adult crickets per week, where each contains up to 97% edible body mass on a dry matter basis before processing them into powder (Nischalke et al. 2020; Adegboye et al. 2021). Crickets are mainly produced for feeding livestock such as poultry and cultured fish in Africa (Nischalke et al. 2020; Tanga et al. 2021). In other countries, they are also produced to feed zoo animals such as birds, reptiles, small mammals, amphibians and fish, or supplied as fish bait, due to their high nutritional value (Makkar et al. 2014; Taufek et al. 2016).

Black soldier flies

The *Hermetia illucens* is the main fly produced under various production systems for animal feeding purposes, due to its rich protein, amino acid and mineral contents as well as high reproductive ability which result in high larval biomass (Nischalke et al. 2020). In East African countries such as Kenya and Uganda, farmers are producing black soldier flies on a small scale and it is an emerging bio-based industry (Orinda et al. 2018). This is because the black soldier flies have higher feed conversion efficiency than livestock, which makes them suitable for rearing on a large scale (Veldkamp et al. 2002; Straub et al. 2019; Babarinde et al. 2021). The fly larvae can convert 30 metric tonnes of agricultural organic waste into 10 metric tonnes in fewer days (Babarinde et al. 2021). It is estimated that they produce about 9780 metric tonnes of dried protein from black soldier flies yearly (Tanga et al. 2021). Hence, this makes them a suitable replacement for soybean and fish meal in animal diets, especially poultry species (Hermans et al. 2021). Furthermore, their organic waste is also recycled and included in animal diets since it is also protein rich. According to Tanga et al. (2021), the mass production of black soldier flies could generate high protein that meets dietary nutrient requirements of livestock including pig, fish and chicken.

Insect production systems in Africa

The insect-rearing systems provide sustainable techniques that will ensure continuous supply of large mass production. Unlike harvesting and capturing of wild insects for supplementation in animal diets, insect farming through various production systems is considered sustainable and consistent (Sanchez-Muros et al. 2014; Babarinde et al. 2021; Mnisi et al. 2022). However, most African countries across East, West and Southern regions have not yet implemented these systems; they are still under investigation focusing on insect production, health risk and legislation (van Huis and Oonincx 2017; Orinda et al. 2018). However, recently the increased animal production costs and readily available organic waste for insect production have stimulated increased interest in commercial production of edible insects as animal feed in Africa (Khalil 2018; Tanga et al. 2021; Adegboye et al. 2021). According to Orinda et al. (2018), examples of production systems that have been recently introduced in Kenya and Uganda to produce edible insects on a small, medium and large-scale, include caging system, pen system, open farming system and captive production system. It has been reported that the systems are mostly initiated by foreign international funders such as *icipe* (International Centre of Insect Physiology and Ecology), GREEiNSECT (Denmark), Flying Food (Dutch) and EntoNUTRI through various projects, mainly for research purposes (Nischalke et al. 2020).

Caging system

This involves growing insects in several suitable cylindrical, drawer or crate containers depending on the capacity of the housing structure. This system, which is mainly used in rearing of crickets, is also called the bucket cage system. However, the system is used for rearing insects on a small and medium scale, where large buckets (80–100 litres), punctured with small holes are placed on elevated shelters with proper air circulation and favourable temperatures. The buckets are elevated to protect insects against predators such as lizards and spiders. In addition, the system facilities and structure can be easily cleaned and disinfected, while allowing full access to the insects during transfer and harvesting (Orinda et al. 2018).

Pens for large-scale production

This system involves using a concrete floor to rear crickets on a large scale; hence, it is called the concrete pen system. It has a large carrying capacity, as well as building structure and facilities that will last longer (Orinda et al. 2018). Sanchez-Muros et al. (2014) also reported that crickets are highly productive when cultured on a large-scale production. Hence, the system involves building cleanable, cheap, and durable large pens with concrete walls (Reverberi 2020). Thereafter, the egg trays or plastic bags are put on the floor of rearing pens to act as a living area for crickets. This area contains clean egg-laying substrates for the females to lay the eggs. The pens or buckets are then covered with a net to prevent predators from entering (Magara et al. 2021). The growth and development of crickets is fast, in that the eggs only take 7–10 days to hatch, and crickets will be ready for harvest between 28 and 35 days. The rearing of crickets on a large scale demands more labour in different departments during the rearing cycle (Halloran et al. 2017).

Production systems under investigation

Other systems still on trial in Africa include open farming systems and captive production systems, which are mainly suitable for rearing black soldier flies on a small, medium or large scale to be included in livestock feeds, particularly for fish, poultry and pig diets (Orinda et al. 2018; Nyangena et al. 2020). The open farming system involves growing flies until larvae to pre-pupal stage under rotting organic waste streams, making them a feasible protein source that can be used in animal diets (Veldkamp et al. 2002; Straub et al. 2019; Babarinde et al. 2021). This system follows natural breeding in an open space sufficient for growing on a small scale. However, the insects are vulnerable to diseases, predators or affected by floods in the rainy season (Orinda et al. 2018). The flies at larvae, however, can produce antimicrobial peptides to protect themselves from microbial infections (Elahi et al. 2022). Proper use of this system stimulates growth and reproduction and enables them to transform organic waste into valuable protein and essential amino acids (Fisher et al. 2020). An open farming system is also recommended by van Huis (2020) who reported that insect production on rearing mediums such as plant weeds or organic residues is considered cheaper and profitable. Nonetheless, the captive system involves rearing insects such as black soldier flies in an enclosed area such as a greenhouse under favourable conditions in terms of temperature and humidity (Orinda et al. 2018).

The absence of insect production systems in most African countries may be due to: poor facilities; lack of proper equipment and strategies to adopt various production systems; lack of knowledge and skills about different insect substrates used and their safety to human and animal health; and effect of climate change that tampers with optimal temperature conditions favourable for high insect productivity (Orinda et al. 2018). Hence there is a need to develop insect farming systems in Africa operating on a large scale to sustainably promote insect industries in the markets (Babarinde et al. 2021).

Insect demand by consumers in Africa

In Africa, the demand for insects is highly influenced by the season of emergence, since the available insects in the market are mainly collected in the bushes especially after first rains when they swarm, rather than being reared in farms (Sankara et al. 2018; Orinda et al. 2018). The harvest of insects from the wild environment could pose a threat to biodiversity conservation. Besides, the wild harvest could not supply insects continuously as they are seasonal. Furthermore, it does not ensure safety since they may contain high anti-nutritional factors including phytate, oxalate and tannins within the digestive tract, which accumulates through feeding of various feed sources. They may also be contaminated with hazardous and toxic materials such as heavy metals, mainly lead, arsenic, cadmium and mercury, which could be obtained from animal manure and crop residues (Mabelebele et al.

2022). However, there is an increase in the marketing of edible insects, stimulated mainly by high insect demand for consumption since they are reported to be rich in nutrients (Ajayi 2012; Mousavi et al. 2020; Ayieko et al. 2021). For instance, currently there is a steady increase in prices as insect sellers became aware of the increased demand for edible insects (Tilami et al. 2020; Nogales-Merida et al. 2019). The elevated demand for edible insects in Africa has also stimulated more interest in farming of insects for both human consumption and animal feeding (Dzerefos et al. 2013; Madau et al. 2020). In addition, the demand for insects and insect products in Western countries is also dependent on migrants from countries in Africa, where insect consumption is a norm (Babarinde et al. 2021). Moreover, there is high import and export of edible insects between neighbouring countries in sub-Saharan Africa; however, this trading is mainly for consumption by humans rather than incorporation in animal diets (Teffo 2007; van Huis et al. 2013). Although there are various edible insects traded in Africa, the information on the quantity demand of each insect is very limited (Dürr and Ratompoarison 2021).

Legislation imposed on insect production in African countries

The government regulation of edible food materials, including insects, is crucial to ensure high quality and safety standards when utilised in human and animal diets (Grabowski et al. 2020). The insect legislation guidelines are mainly focused on regulating safety, hygiene, insect use as animal feed, and concentration levels of harmful and toxic substances (Abdullahi et al. 2021). For edible insects to be recognised and acknowledged in the market, safety must be properly assessed and authorised as the priority by government food regulatory bodies of various countries (Goumperis 2019; Abdullahi et al. 2021). Furthermore, the regulations on production systems used and insect slaughter or killing method, as well as the use of organic wastes as substrates for edible insects, such as the legal frameworks used in United States and Western countries, must also be considered when farming with edible insects (Pali-Schöll et al. 2019; Mariod 2020; Abdullahi et al. 2021). It has been reported that insect production without any legislations and policies could result in poor rearing management strategies and sustainable methods of producing edible insects (Abdullahi et al. 2021; Macheka et al. 2022).

Currently, almost all African countries have few (in Kenya and Uganda) or no government laws or legislative frameworks focusing on approval of edible insect production and their safe use as food or feed (van Huis 2017). According to Grabowski et al. (2020), food laws in Africa are either lacking or outdated; hence, more attention is given to food security while less focus is on food safety, more specifically the chemical, microbial and antibiotic risks associated with utilisation of edible foods such as insects. For instance, it has been reported that breeding, marketing and food safety legislation strategies and guidelines for farming of edible insects such as crickets and locusts as animal feed source are yet to be developed and adopted by governments (Babarinde et al. 2021; Mézes and Erdélyi 2020: Mariod 2020; Abdullahi et al. 2021). However, the promotion of insect production in most countries is mainly supported by research institutions through conducting trials, rather than by governments and businesses (Nischalke et al. 2020). The issue of permanent laws and policies on the safe farming of insects was emphasised and addressed in the recent International Food Safety Conference held in Ethiopia in 2019 (Grabowski et al. 2020). Additionally, other countries such as Rwanda are also planning on drafting and implementing production and safety legislation standards which will be effective in producing a large mass of insects at a higher rate (Abdullahi et al. 2021).

Nevertheless, East African countries such as Kenya and Uganda have agreed and approved the potential use of all edible insects, mainly black soldier fly *(Hermetia illucens)* larvae, as animal feed without any restriction on safety and waste substrate they use (Nyangena et al. 2020), unlike in Europe which only approved selected insects and feed substrates to be used for insect farming (Tanga et al. 2021). The legislation standards mainly focus on regulating safety of how edible insects reared for animal feeding purposes are produced, handled and processed (Tanga et al. 2021). Currently, Kenyan insect production legislation guidelines are lagging; however, they are boosted by operations research institutions in the country. Furthermore, the active policies approved by the governments of Kenya (Kenya Bureau of Standards (2016) (KEBS)) and Uganda (Ugandan National Bureau of Standards (2017) (UNBS)) consider black soldier flies as a good opportunity to initiate new markets of insects reared for animal feeding (Nischalke et al. 2020).

Apart from that, there are approved government laws and regulations in Africa focusing on pest management practices as well as protection of natural resources, including the harvesting or collection of edible insects in the wild (Grabowski et al. 2020). According to Thomas (2013), the regulation guidelines for this legislation emphasised that insects should be monitored, controlled and reserved through rotational harvesting in various sites, regulating the number of harvesters, when and where to harvest and insect quantity to be harvested. These restrictions are applied mainly because deforestation and overharvesting of edible insects by humans without any regulations could adversely inhibit the sustainable use of insect food and feed (Mufandaedza et al. 2015; Lange and Nakamura 2021; Orinda et al. 2018; Babarinde et al. 2021; Mnisi et al. 2022). In addition, there are international laws and regulations (International Plant Protection Convention) imposed on the introduction of insects as pests in case they escape and pose danger on humans, animals, biodiversity or plants in a country (van Huis and Oonincx 2017).

The benefits of producing edible insects as animal feed in Africa

Edible insects as food and feed provide economic, environmental and health benefits (Lange and Nakamura 2021). Although insects such as black soldier flies are not consumed by humans, they indirectly form part of their diets when incorporated in animal feeds (Nyangena et al. 2020). Generally, insects and insect meals have been reported to contain a high level of crude protein and amino acid content, which makes them a suitable replacement for soybean and fish meal in animal diets, especially poultry species (Adli 2021; Babarinde et al. 2021; Adegboye et al. 2021). In addition, they could convert organic waste into valuable protein, hence could potentially serve as a sustainable alternative protein feed source in animal diets (van Huis et al. 2013; Veldkamp and Bosch 2015; Vrabec et al. 2015; Orsi et al. 2019; Freccia et al. 2020; Tilami et al. 2020). More so, edible insects such as yellow mealworm (*Tenebrio molitor*) at larvae stage contain chitin, a fibrous substance that could be beneficial in improving the health status of poultry species, utilised as a substitute for antibiotics in poultry diets by reducing the accumulation of harmful microbial populations, hence preventing pathogen infections (Bovera et al. 2015; Motte et al. 2019; Selaledi et al. 2020; Terova et al. 2021; Elahi et al. 2022). However, apart from having nutritional and health benefits, insects could also be used as medicine, since they contain antimicrobial, anti-inflammatory and antibacterial properties (Babarinde et al. 2021.

Nonetheless, farming of insects has been reported to be cost-effective since it requires less land and water consumption, and has reduced greenhouse emissions with elevated feed conversion efficiency compared to livestock production (Mishyna et al. 2021; Lange and Nakamura 2021; Adegboye et al. 2021). It poses less threat on climate change due to less greenhouse and ammonia emissions than livestock such as ruminants (Govorushko 2019; Lange and Nakamura 2021). Consequently, it helps to preserve wild insects and the environment, as well as reducing competition for food between humans and animals, since scarce and expensive conventional feedstuffs such as fish, soya and maize will be readily available to feed the ever-growing human population (Tanga et al. 2021; Adegboye et al. 2021; Lange and Nakamura 2021). Moreover, the rearing of edible insects on a large scale further results in job creation, production of more organic fertilisers and improved soil health, while generating huge profits, especially in the poultry production industry (Tanga et al. 2021). The wastes produced when farming insects on a large scale could be effectively utilised as a source of organic fertiliser in crop production (DiGiacomo and Leury 2019; Babarinde et al. 2021). Hence, the production of edible insects could prove to be environmentally friendly and sustainable to help reduce food insecurity (Lange and Nakamura 2021; Dürr and Ratompoarison 2021).

Major challenges of producing edible insects as animal feed in Africa

The health and safety issues, particularly the anti-nutrient properties present in insect bodies, require attention when rearing insects on a large scale at the farm level (Dobermann et al. 2017; Salter 2019; Tang et al. 2019; Abdullahi et al. 2021). However, there is limited information about the safety of edible insects produced as animal feeds in Africa (Lange and Nakamura 2021; Abdullahi et al. 2021).

Insect farming could be negatively influenced by contaminants, such as pathogens, bacteria, chemicals, toxins, and heavy metals, hence this also requires attention as they affect the nutritional value, health status and acceptability of insect meals (DiGiacomo and Leury 2019; Abdullahi et al. 2021). The insects produced at the farm level are reported to be vulnerable to fungal and bacterial diseases that could be acquired from contaminated local substrates (Tanga et al. 2021; Potgieter and Ramalivhana 2020). For instance, crickets are reported to be vulnerable to *Rickettsiella* sp. which is a harmful bacteria that causes growth reduction of various cricket species reared under different production systems (Nischalke et al. 2020). However, the presence of harmful pathogens and microbial contaminations could be inhibited through various processing techniques, such as oven baking, boiling, smoking, roasting, frying and cooking, consequently reducing the health risks of utilising insects in animal diets (Tanga et al. 2021).

Edible insects could also be associated with having biological and chemical substances which could pose health risks to animals consuming them (Lange and Nakamura 2021). Therefore, it is vital to consider the presence of anti-nutrients, pathogens, allergenic and toxic substances in reared edible insects (Rumpold and Schluter 2013; Adegboye et al. 2021), to reduce spreading harmful contaminants or diseases through the food chain (Orinda et al. 2018). This includes various anti-nutritional factors such as chitin (Dobermann et al. 2017; Kim et al. 2019), since they adversely influence the availability and accessibility of nutrients present within the insect (Oonincx and Finke 2021). However, the lack of knowledge, resources and skills on how to rear insects have also been reported to be the major challenge that inhibits insect production in Africa (Nischalke et al. 2020; Babarinde et al. 2021; Lange and Nakamura 2021).

Conclusion

It was concluded that most African edible insects could provide sufficient amounts of protein, energy, fats, essential amino acids, minerals and vitamins to meet the nutrient requirements of livestock, especially poultry species. However, consistent production in large quantities at low health risks cannot be maintained due lack of production systems, government legislation and policies in African countries. Hence, there is a need to implement new or update existing farming systems and legislation frameworks that will ascertain the sustainability of edible insects as animal feeds. In addition, it is also advisable to consider finding a suitable, highly nutritive, and readily available insect substrate that does not compete with humans and livestock for consumption.

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Author contributions statement

Substantial contributions to the conception and design of the work: SDK and MM.
Drafting of data for the work: SDK
Revising the review article critically for important intellectual content: MM, NAS, and TGM
Final approval of the version to be published: MM, SDK, NAS, and TGM
Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: MM and SDK

Data availability statement

The data used in this review article was acquired from recently published scientific literature from different journals. Databases were accessed using electronic data sources such as Directory of Open Access Journals (DOAJ), Research Gate, Science Direct, and Google Scholar. In addition, the citations included in articles from the databases were used to search for further relevant literature.

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