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Advances in production of crickets as food and animal feed

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1 Introduction

The global human population is expected to grow to 9.7 billion by 2050 (Grafton et al., 2015; Kemsawasd et al., 2022). However, climate change threatens production of the quantities of food required to feed this growing population, leading to increased food insecurity (Kousar et al., 2021). It is estimated that approximately 500 million people, especially in Africa and Asia, are suffering from malnutrition (Kogan et al., 2019). Insects present a suitable alternative food source that can alleviate increasing food insecurity, given advantages such as nutrient profile, availability, low production cost and reduced vulnerability to climate change (van Huis et al., 2013).

Crickets belong to the family Gryllidae (Orthoptera) which contains more than 500 species worldwide (van Huis, 2020). Crickets are among the most commonly consumed edible insects either as human food or livestock feed

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(van Huis, 2013; Magara et al., 2021). They are nutrient dense with high levels of proteins, fats, lipids, minerals and vitamins necessary for human nutrition and health (Magara et al., 2021). They also have a short life cycle compared with conventional livestock and are relatively easy to produce in large quantities (Gahukar, 2011). Given low production costs, cricket farming can form a source of livelihood for many households (Halloran et al., 2018). However, consumption of crickets is more widespread in Africa and Asia compared with western countries (Raheem et al., 2018). The cost of a kilogram of crickets varies widely between US$1.86 and US$40.0 (with premium pricing in many developed countries).

2 Edible cricket species

Although the consumption of crickets is an ancient practice that is widespread across Africa, Asia and Latin America, continuing research on their nutritional value and increasing food insecurity has led to the recognition of crickets as a food source in Australia, the Americas and Europe in recent years (Magara et al., 2021). This has been further enhanced by legislation in, for example, the European Union (EU) that recognizes edible crickets as a novel food source capable of reducing malnutrition and food insecurity (EFSA Scientific Committee, 2015; Magara et al., 2021).

There are approximately 62 edible cricket species utilized as human food or livestock feed across the globe (Magara et al., 2021). Of these, Asian, African and American consumers can choose between 41, 26 and 5 species of crickets, respectively, with 4 species consumed in both Europe and Australia. The regional distribution of cricket consumption is 25 countries in Africa, 13 in Asia, 5 in the Americas and 4 in Europe as well as Australia and New Zealand.

3 Crickets as food and feed

Crickets are reared for use as human food or feed for domesticated animals, pets, insectivorous amphibians and reptiles (van Huis, 2020). The most consumed species include *Acheta domesticus*, *Gryllodes sigillatus*, *Gryllus assimilis*, *Gryllus bimaculatus*, *Teleogryllus testaceus (Gryllus testaceus)* and *Scapsipedus icipe* (Verner et al., 2021).

3.1 Crickets as food

A. domesticus and *G. bimaculatus* are domesticated for use as food in different countries in Asia and Africa (Halloran et al., 2018). These two species are preferred for rearing for a number of reasons. *A. domesticus* can be reared on diverse diets, require low maintenance, and exhibit low disease incidence and high nutritional value, whereas *G. bimaculatus* mature quickly, are large in

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size and easy to sell (Halloran et al., 2017). In Thailand, there are approximately 20 000 farmers who produce more than 7000 tonnes of crickets annually (Hanboonsong et al., 2013). The most reared species in Thailand include *G. bimaculatus, Teleogryllus occipitalis, G. testaceus* and *A. domesticus*, while *G. testaceus* is also farmed as food in Indonesia (Fuah et al., 2015; van Huis, 2020).

Other cricket species used as food include *Brachytrupes portentosus*, *Gymnogryllus* sp., *Velarifictorus* sp. and *Modicogryllus confirmatus* in Thailand; *Brachytrupes membranaceus colosseus*, *Modicogryllus* sp. and *Fryerius* sp. in Madagascar; and *B. membranaceus* in Kenya (Fuah et al., 2015; Magara et al., 2021; van Itterbeeck et al., 2019). These species are, however, collected from the wild.

Crickets can be consumed whole or dried and processed into powder to be used as an ingredient to fortify products (Halloran et al., 2016). In Thailand, for example, cricket powder is exported to European countries, while whole crickets are consumed locally. Crickets have been used in the formulation of bread, cookies and porridge flour with high consumer acceptability in developing countries (Bartkiene et al., 2022). Different industries in western countries formulate various types of cricket-based foods in the form of dried cricket and cricket flour (Kemsawasd et al., 2022).

3.2 Crickets as feed

Different species of crickets are used as animal feed or feed ingredients across the globe (Table 1). Although crickets can be consumed directly as human food, their use as animal feed is highly profitable when they are reared using organic waste side streams and weeds (Armansyah Handayani, 2020; Miech et al., 2016). Crickets can be given to animals whole or crushed into powder and used as an ingredient in the production of animal feed. The inclusion of

Table 1 Cricket species used as animal feed

Cricket species	Animal feed	References
*A. domesticus**	Fish, poultry, pet food	Kovitvadhi et al. (2019); Lee et al. (2017); Miech et al. (2016); Ververis et al. (2022)
B. portentosus	Poultry	Abdul et al. (2012)
*G. assimilis**	Fish, pet food	Alfaro et al. (2019); Weissman et al. (2012)
G. bimaculatus	Fish, poultry, pet food	Kovitvadhi et al. (2019); Taufek et al. 2018); Weissman et al. (2012)
*G. sigillatus**	Pet food, fish	Jarett et al. (2019)
G. testaceus	Pigs, poultry	Miech et al. (2017); Wang et al. (2005)
G. veletis	Not specified	Magara et al. (2021)
T. emma	Not specified	Ghosh et al. (2017)

*Approved for the production of aqua feed in the EU (Commission Regulation (EU), 2017).

crickets in livestock feed provides a cheaper alternative feed source that can significantly reduce the cost of livestock production (van Huis et al., 2013). *A. domesticus*, *G. sigillatus* and *G. assimilis* are e.g. authorized for use in the production of processed animal protein for aquaculture feeds in the EU (Bertola & Mutinelli, 2021).

4 Production systems for crickets

As noted earlier, Thailand is among the leading nations involved in the production of crickets as food, with more than 20 000 farmers involved in the enterprise. However, cricket farming remains a small-scale activity here (Halloran et al., 2016). Halloran et al. (2018) describe the different types of cricket farming systems found in Thailand, Kenya, the Democratic Republic of Congo (DRC), Cambodia and the Lao People's Democratic Republic (Lao PDR). The concrete block pen system is the most commonly used system in Thailand. Pens can be rectangular or cylindrical, constructed with lightweight concrete blocks and a concrete floor, usually covered with nylon netting to prevent the escape of crickets and entry of predators. In Cambodia, medium-scale farmers use rectangular brick and cement pens that are covered with tiles to prevent crickets from escaping. The upper part of the pen is covered with a mosquito net while the base has a water tunnel to deter predators. Small-scale farmers on the other hand use 60 L containers to breed crickets.

Rectangular and small cylindrical concrete pens, rectangular boxes with wooden frames and walls made of plywood, gypsum board, plastic sheets or furniture backing board are used for rearing crickets in Lao PDR. Plastic boxes of different sizes and 100 L plastic buckets have been tested in DRC and Kenya, respectively. Concrete pens, pens built with mud, wash basins and rearing crate systems are also used in Kenya. The rearing systems are fitted with egg cartons to provide shelter to crickets. These cartons are usually elevated to prevent accumulation of food and faecal material.

Larger-scale, automated cricket production occurs in western countries. The Aspire Food Group in North America e.g. has established a 100 000 square feet, fully automated cricket production and processing plant that is expected to produce 10 000 tonnes of crickets per year (Liceaga, 2022). Other cricket farming companies such as Cricket Crackers, Cricket Foods and The Cricket Girl among others have been established in Europe and North America with annual production capacity ranging between 200 and 12 000 metric tonnes (Kemsawasd et al., 2022). There is increasing recognition that, in addition to food and feed, crickets can produce multiple high-value market products such as protein, oils, chitin/chitosan and frass fertilizer.

5 Cricket-rearing diets

Crickets have been reared on conventional livestock feed, weeds, industrial and agricultural by-products and food waste (Kuo & Fisher, 2022; Magara et al., 2019; Sorjonen et al., 2019). Cricket rearing commonly uses cereal grain feed, soybean and poultry feed (Jucker et al., 2022). The growth of cricket farming in Thailand has led to the formulation of around five different brands of specialist cricket feed (Halloran et al., 2016). However, these feeds are very similar in composition to chicken feed (Halloran et al., 2017). The feed is supplemented with different vegetable leaves such as pumpkin, cassava and amaranth, in addition to fruit peelings such as those of pineapple, banana, mango, pawpaw and avocado (Halloran et al., 2018).

In order to reduce feed costs, alternative dietary ingredients have been tested for the production of crickets with varied results. Agro-industrial by-products present a viable feed source for the sustainable production of farmed insects (Jucker et al., 2022; Kuo & Fisher, 2022). Human waste by-products are inexpensive, available in large quantities and have a good nutrient profile, and can lower the cost of insect production and minimize environmental impact (Jucker et al., 2022). Orthopterans such as crickets are well adapted to converting these by-products into accessible sources of nutrients (Van Peer et al., 2021).

Crickets reared on diets of pure food waste resulted in a low survival yield of 6%, while diets supplemented in part with food waste yielded 77% survival. Pure weed diets and commercial feed supplemented with weeds resulted in 18% and 85% survival of crickets, respectively. Diets comprising pure agricultural by-products and diets comprising conventional feed supplemented with agricultural by-products led to cricket survival yields of 34% and 60%, respectively (Kuo & Fisher, 2022). These variations arose as a result of the diverse nutrient composition of diet types which influenced nutrient accessibility. As such, appropriate diets for optimal cricket performance should supply high-quality nutrition to enhance fitness parameters and cricket survival rates.

Optimal cricket performance has been observed for diets containing 20–30% crude protein and 4–20% crude fats (Capparos Megido et al., 2016; Lundy & Parrella, 2015; Magara et al., 2019; Vaga et al., 2019). Significant amounts of oleic and linoleic fatty acids and a high carbohydrate content are also critical for improved cricket performance (Oonincx et al., 2015; Orinda et al., 2017; Sorjonen et al., 2019; Vaga et al., 2019). High amounts of indigestible fibre in the feed is negatively correlated with cricket growth and survival, thus highlighting the need for inclusion of considerable amounts of fibre in cricket diets (Lundy & Parrella, 2015; Magara et al., 2019; Orinda et al., 2017; Vaga et al., 2020).

6 Nutrient composition of edible cricket species

Crickets have a rich profile of nutrients such as proteins, carbohydrates, lipids, vitamins and minerals. Crickets are a rich source of proteins (50–72%), fats (10–46%) and energy (452–547 kcal/100 g) (Table 2). They also contain considerable amounts of fibre, ash and carbohydrates. The nutritional content of crickets is influenced by species, developmental stage, rearing substrate/diet, sex, habitat and processing methods (Musundire et al., 2014; van Huis et al., 2013).

Edible crickets exhibit a rich profile of fatty acids (Table 3). The most abundant saturated fatty acids recorded in edible cricket species include palmitic acid (23–31%) and stearic acid (7–17%); monounsaturated fatty acids include oleic acid (11–30%) and palmitoleic acid (0.3–11%), while linoleic acid (23–41%) was the most prevalent polyunsaturated fatty acid. The inclusion of crickets in diets can thus supply polyunsaturated acids that cannot be produced by mammals (Govorushko, 2019). Polyunsaturated acids have been shown to provide protective effects against cardiovascular diseases, cancer and diabetes (Govorushko, 2019; Yorek, 2018).

Edible cricket species also contain varying amounts of amino acids (Table 4). All of the essential amino acids have been reported in *A. domesticus* and *G. assimilis* (Bednářová et al., 2013; Magara et al., 2021). Leucine was the most abundant essential amino acid recorded in edible cricket species except for *G. assimilis*, which had higher levels of lysine. Some of the essential amino acids found in crickets are absent in commonly consumed plant protein sources, indicating that inclusion of crickets in a diet can help to mitigate amino acid deficiencies that cause malnutrition in developing countries (Ghosh et al., 2017; Zielińska et al., 2015). Crickets can also be used as a source of essential amino acids in the fortification of food products to alleviate malnutrition (Köhler et al., 2019). Glutamic acid was the most abundant non-essential amino acid occurring in *A. domesticus*, *G. bimaculatus*, *G. assimilis* and *G. testaceus* (Ghosh et al., 2017; Magara et al., 2021; Wang et al., 2004; Zielińska et al., 2015).

Crickets contain diverse quantities of macro- and microminerals essential for human health (Table 5). Significant quantities of phosphorus (702–900 mg/100 g) have been reported in *A. domesticus*, *G. bimaculatus* and *G. sigillatus* while high levels of sodium (395 mg/100 g) and potassium (871 mg/100 g) occur in *S. icipe* and *G. sigillatus*, respectively (Murugu et al., 2021; Ribeiro et al., 2019; Udomsil et al., 2019). All the edible cricket species contain zinc (5–24 mg/100 g) and iron (3–12 mg/100 g). The regular consumption of crickets can decrease the large number of cases of zinc and iron deficiencies that are common among children and women of child-bearing age in developing countries (Mwangi et al., 2018).

Diverse quantities of vitamins have been reported in four species of commonly consumed cricket species (Table 6). *A. domesticus* contains high

Table 2 Proximate composition of the most commonly consumed edible cricket species

	Composition of cricket species					
Component	*A. domesticus*	*G. assimilis*	*G. bimaculatus*	*G. sigillatus*	*S. icipe*	*G. testaceus*
Crude protein (%)	71.7 ± 0.5	57.2	58.2 ± 3.7	70.0 ± 1.7	50.2 ± 2.1	63.3
Crude fat (%)	10.4 ± 0.1	34.3	46.0 ± 2.9	18.2 ± 0.7	35.7 ± 2.6	10.3
Crude fibre (%)	4.6 ± 0.2	NR	8.4 ± 2.3	3.7 ± 0.5	5.7 ± 1.4	5.2
Moisture (%)	6.3 ± 0.0	NR	3.0 ± 0.0	NR	NR	5.0
Ash (%)	5.4 ± 0.3	4.1	5.4 ± 0.1	4.7 ± 0.4	5.3 ± 0.0	5.6
Carbohydrates (%)	1.6 ± 0.1	8.6	0.1 ± 0.0	0.1 ± 0.0	NR	NR
NFE	NR	1.2	10.6	NR	NR	NR
Energy (Kcal/100 g)	NR	546.8	529.2 ± 3.2	452.0 ± 4.3	512.7 ± 1.7	NR
References	Udomsil et al. (2019)	Araujo et al. (2018); Bednářová et al. (2013)	Ghosh et al. (2017); Murugu et al. (2021); Udomsil et al. (2019)	Zielińska et al. (2015)	Murugu et al. (2021)	Shah & Wanapat (2021); Wang et al. (2004)

NR: not reported; NFE: nitrogen-free extract.

Table 3 Fatty acid composition of the most commonly consumed edible cricket species

Fatty acids (%)	*A. domesticus*	*G. assimilis*	*G. bimaculatus*	*G. sigillatus*	*S. icipe*	*T. testaceus*
Enanthic (C7:0)	NR	NR	0.21 ± 0.0	NR	0.09 ± 0.0	NR
Caprylic (C8:0)	NR	NR		NR	0.06 ± 0.0	NR
Capric (C10:0)	0.00	0.03	0.02 ± 0.0	NR	0.04 ± 0.0	NR
Undecanoic (C11:0)	NR	NR	0.35 ± 0.1	NR	0.26 ± 0.0	NR
Lauric (C12:0)	0.10 ± 0.0	0.12	0.35 ± 0.0	0.1 ± 0.0	0.31 ± 0.0	0.54 ± 0.0
Tridecanoic (C13:0)	NR	0.02	0.42 ± 0.1	NR	0.22 ± 0.1	NR
Myristic (C14:0)	0.44 ± 0.0	1.28	3.7 ± 0.6	1.65 ± 0.1	5.43 ± 0.9	0.39 ± 0.0
Myristoleic (C14:1)	0.03 ± 0.0	0.06	0.09 ± 0.0	0.09 ± 0.0	NR	NR
Pentadecanoic (C15:0)	0.11 ± 0.0	0.37	NR	0.24 ± 0.0	0.08 ± 0.0	10.18 ± 0.2
Palmitic (C16:0)	22.65 ± 0.4	25.58	31.18 ± 0.7	23.5 ± 0.7	23.89 ± 0.6	
Palmitoleic (C16:1)	0.34 ± 0.0	1.92	9.22 ± 0.6	3.78 ± 0.2	11.14 ± 1.0	3.11 ± 0.1
Margaric (C17:0)	0.12 ± 0.0	0.57	1.44 ± 0.1	0.32 ± 0.0	1.44 ± 0.1	NR
Heptadecenoic (C17:1)	0.24 ± 0.0	0.19	NR	0.29 ± 0.0	NR	NR
Stearic (C18:0)	8.54 ± 0.0	14.07	14.71 ± 1.4	7.35 ± 0.3	17.26 ± 0.6	2.63 ± 0.1
Oleic acid (C18:1)	20.18 ± 0.0	25.03	10.94 ± 0.81	29.14 ± 1.5	11.4 ± 0.8	29.58 ± 0.2
Linoleic (C18:2)	41.39 ± 0.3	26.13	23.56 ± 0.3	29.78 ± 0.8	23.56 ± 0.3	37.82 ± 0.2
Linolenic (C18:3)	NR	1.60	0.32 ± 0.0	NR	0.21 ± 0.1	10.12 ± 0.1
α-linolenic (C18:3n3)	1.11 ± 0.0	NR	NR	2.13 ± 0.0	NR	NR
Nonadecanoic (C19:0)	NR	NR	0.83 ± 0.1	NR	0.73 ± 0.1	NR

Arachidic (C20:0)	NR	0.56	0.01 ± 0.0	0.40 ± 0.0	0.00	NR
Eicosenoic (C20:1)	NR	0.24	NR	1.03 ± 0.1	NR	NR
Eicosadienoic (C20:2)	0.00	0.44	NR	NR	NR	NR
C20:3	NR	0.01	0.79 ± 0.0	NR	0.86 ± 0.1	NR
C20:4	0.01 ± 0.0	0.21	0.02 ± 0.0	NR		NR
C20:5	NR	0.38	0.07 ± 0.0	NR	0.08 ± 0.0	NR
Heneicosylic (C21:0)	0.24 ± 0.0	0.03	0.32 ± 0.1	0.13 ± 0.0	0.5 ± 0.1	NR
Behenic (C22:0)	NR	0.57	0.01 ± 0.0	0.07 ± 0.0	0.37 ± 0.0	NR
C22:1	0.52 ± 0.0	0.05	NR	NR	NR	NR
C22:2	0.11 ± 0.0	0.03	NR	NR	NR	NR
C23:0	0.02 ± 0.0	0.22	NR	NR	NR	NR
Lignoceric (C24:0)	NR	NR	0.26 ± 0.0	NR	0.28 ± 0.0	NR
others	3.84	4.80	NR	NR	NR	NR
SFA	32.22	43.72	57.60	33.74 ± 0.8	50.96	13.74
MUFA	21.72	27.49	23.24	34.33 ± 0.1	24.33	32.69
PUFA	42.64	28.80	19.16	31.91 ± 0.1	24.71	47.94
	Paul et al. (2017)	(Mlcek et al. (2018)	Murugu et al. (2024)	Zielińska et al. (2015)	Murugu et al. (2024)	Magara et al. (2021); Wang et al. (2004)

NR: not reported.

Table 4 Amino acid composition of the most commonly consumed edible cricket species

Amino acid	*A. domesticus* (g/100 g)	*G. assimilis* (g/100 g)	*G. bimaculatus* (g/100 g)	*G. sigillatus* (mg/g)	*S. icipe* (µg/100 mg)	*G. testaceus* (g/100 g)
Essential amino acids						
Histidine	2.3 ± 0.1	1.3 ± 0.4	2.5 ± 0.1	17.2 ± 0.2	10.8 ± 0.9	1.9 ± 0.0
Isoleucine	4.5 ± 0.2	2.1 ± 0.7	2.2 ± 0.0	26.6 ± 0.5	43.4 ± 10.6	3.1 ± 0.0
Leucine	9.8 ± 0.4	5.0	4.0 ± 0.1	57.8 ± 1.1	66.2 ± 12.5	5.5 ± 0.1
Lysine	5.4 ± 0.0	7.9 ± 0.6	2.4 ± 0.0	38.4 ± 0.9	18.2 ± 3.9	4.8 ± 0.1
Methionine	1.4 ± 0.1	0.6 ± 0.2	0.3 ± 0.0	15.9 ± 0.8	NR	1.3 ± 0.1
Phenylalanine	3.0 ± 0.3	0.7 ± 0.2	1.8 ± 0.0	22.0 ± 0.2	NR	2.9 ± 0.1
Threonine	3.6 ± 0.0	3.6 ± 0.6	2.0 ± 0.0	36.8 ± 0.5	NR	2.8 ± 0.1
Tryptophan	0.6 ± 0.1	1.0 ± 0.2	NR	NR	NR	NR
Valine	1.1	4.6 ± 0.6	3.2 ± 0.0	47.0 ± 1.0	29.1 ± 7.8	4.4 ± 0.0
Non-essential amino acids						
Arginine	6.1 ± 0.0	8.6	3.6 ± 0.0	46.6 ± 0.6	13.6 ± 1.1	3.7 ± 0.1
Serine	1.0	0.6 ± 0.2	2.7 ± 0.0	40.4 ± 0.5	NR	3.7 ± 0.1
Proline	1.2	1.3 ± 0.7	2.0 ± 0.0	54.2 ± 0.8	19.2 ± 6.1	4.5 ± 0.1
Alanine	8.9 ± 0.1	4.0 ± 0.6	5.6 ± 0.0	58 ± 0.8	NR	5.6± 0.1
Cysteine	0.8 ± 0.0	0.7 ± 0.1	5.1	11.1 ± 0.2	25.4 ± 8.0	1.0 ± 0.0
Tyrosine	1.0	5.4 ± 0.7	2.7 ± 0.0	31.8 ± 0.4	23.8 ± 5.8	3.9 ± 0.0
Glycine	1.0	2.4	3.3 ± 0.0	40.7 ± 0.4	NR	3.6 ± 0.1
Glutamic acid	10.5 ± 0.1	3.6	6.4 ± 0.1	106.6 ± 1.4	9.6 ± 0.3	9.1 ± 0.3
Aspartic acid	7.8 ± 0.9	3.0	3.6 ± 0.0	72.8 ± 1.0	NR	3.7 ± 0.1
References	Magara et al. (2021)	Bednářová et al. (2013)	Ghosh et al. (2017)	Zielińska et al. (2015)	Murugu et al. (2021)	Magara et al. (2021); Wang et al. (2004)

NR: not reported.

Table 5 Mineral content of the most commonly consumed edible cricket species

Minerals (mg/100 g)	*A. domesticus*	*G. assimilis*	*G. bimaculatus*	*G. sigillatus*	*S. icipe*
Calcium	149.8 ± 7.2	45.3	72.7 ± 1.7	117.3 ± 12.2	66.1 ± 1.6
Potassium	389.9 ± 1.4	NR	39.5 ± 0.9	870.9 ± 18.6	66.3 ± 0.3
Magnesium	136.6 ± 4.9	27.2	29.1 ± 0.6	42.7 ± 1.8	35.6 ± 2.0
Phosphorus	899.9 ± 36.2	NR	702.0 ± 6.4	782.1 ± 86.7	NR
Sodium	101.4 ± 7.8	NR	166.5 ± 0.0	298.1 ± 18.5	395.4 ± 41.6
Iron	8.8 ± 3.9	2.8	12.3 ± 5.4	4.7 ± 0.3	10.7 ± 0.6
Zinc	19.6 ± 0.8	5.2	23.7 ±1.3	16.8 ± 0.3	19.2 ± 0.6
Manganese	4.4 ± 0.1	1.4	108.5 ± 18.3	2.9 ± 0.4	95.7 ± 17.2
Copper	4.9 ± 0.4	0.7	8.3± 1.5	4.9 ± 0.5	7.9 ± 0.7
Selenium	NR	NR	NR	0.1 ± 0.0	NR
Cobalt	NR	NR	4.4 ± 1.6	NR	5.1 ± 2.6
References	Udomsil et al. (2019)	Araujo et al. (2018)	Murugu et al., (2021); Udomsil et al. (2019)	Ribeiro et al. (2019)	Murugu et al. (2021)

NR, not reported.

Table 6 Vitamin composition of commonly consumed edible crickets

Vitamins (mg/100 g)	*A. domesticus*	*G. assimilis*	*G. bimaculatus*	*S. icipe*
Vitamin A/retinol	<67.00	2.90 ± 0.1	0.03 ± 0.0	0.04 ± 0.0
Vitamin B1/thiamin	0.04	NR	0.42 ± 0.0	0.01 ± 0.0
Vitamin B2/riboflavin	3.41	0.23 ± 0.1	0.89 ± 0.5	0.54 ± 0.1
Vitamin B3/niacin	3.84	NR	1.10 ± 0.2	NR
Vitamin B5/ pantothenic acid	2.30	NR	NR	NR
Vitamin B6/pyridoxine	0.23	NR	5.28 ± 0.9	1.6 ± 0.4
Vitamin B7/biotin	0.02	NR	NR	NR
Vitamin B9/folic acid	0.15	NR	0.51 ± 0.1	0.41 ± 0.1
Vitamin B12	0.01	10.00 ± 0.0	NR	NR
Vitamin C	3.00	1.01 ± 0.6	NR	NR
Vitamin D	<17.15	NR	NR	NR
Vitamin E (α & γ tocopherol)	1.32	30.00 ± 0.0	NR	NR
References	Magara et al. (2021)	Oibiokpa et al. (2017)	Murugu et al. (2021)	Murugu et al. (2021)

NR: not reported.

quantities (≥ 3 mg/100 g) of riboflavin, niacin and vitamin C, while higher quantities of tocopherol and pantothenic acid occur in *G. assimilis* and *G. bimaculatus*, respectively (Magara et al., 2021; Murugu et al., 2021; Oibiokpa et al., 2017). Although vitamins are required for metabolism, they cannot be produced by the human body and must therefore be supplied through the diet (Alamu et al., 2013; Kekeunou et al., 2020). A deficiency of vitamins and minerals can cause adverse health outcomes that account for almost a million deaths annually (Zhou et al., 2022). The consumption of crickets can therefore supplement vitamin sources to improve human nutrition and health outcomes.

7 Safety and disease issues in cricket production

Crickets have been screened for potential hazards both in raw and processed forms and have been found to contain possible microbial hazards. Pathogenic bacteria such as *Salmonella* and *Shigella* sp., as well as spore-forming bacteria such as *Bacillus*, *Paenibacillus* and *Psychrobacillus*, have been isolated from raw crickets, as well as fungi such as *Aspergillus flavus*, *Cladosporium sphaerospermum* and *Aspergillus sydowii* (Belluco et al., 2013; Fernandez-Cassi et al., 2019; Nyangena et al., 2020). Unprocessed *A. domesticus* was found to contain high levels of aerobic mesophilic spore-forming bacteria (2.6–4.4 cfu/g), *Enterobacteriaceae*, lactic acid bacteria, *Bacillus cereus*, *Staphylococcus aureus*, yeast and mould (Ververis et al., 2022). *G. assimilis* can contain *Coprococcus*, *Lactococcus* and *Candidatus azobacteroides* (Aleknavicius et al., 2022). Mycotoxin-producing fungi such as *Aspergillus*, *Candida*, *Kodamaea*, *Lichtheimia*, *Terapisipora*, *Trichospora* and *Trichoderma* have been isolated from reared crickets (Vandeweyer et al., 2018).

Crickets are affected by insect viruses that are fatal and can annihilate the commercial rearing of some cricket species. *A. domesticus* is infected by *A. domesticus* densovirus, *A. domesticus* mini ambidensovirus, ambisense densovirus, *A. domesticus* volvovirus and *A. domesticus* Iflavirus. Viral pathogens described in *G. bimaculatus* include *Densovirus*, *Iridovirus*, *Nudivirus* and *Cripavirus*. *G. bimaculatus* shows high susceptibility to *Iridovirus*. *A. domesticus* densovirus has been isolated from *G. assimilis*, while *Iridovirus*, *A. domesticus* densovirus and *A. domesticus* volvovirus have been detected in *G. sigillatus* (Bertola & Mutinelli, 2021; Jakob et al., 2002; Szelei et al., 2011). Nudivirus is also fatal to other cricket species such as *Teleogryllus commodus*, *Teleogryllus oceanicus* and *G. campestris* (van Huis, 2020); however, these viruses are unlikely to threaten human health (Kemsawasd et al., 2022).

Limited biological hazards occur in processed crickets, though fungi can pose a risk during the production process (SLU et al., 2018). High aerobic mesophilic counts, fungi and some bacterial pathogens, such as *Bacillus* and *Staphylococcus*, have been isolated from processed crickets (Ververis et al., 2022); however, the microbial load was shown to reduce following heat processing (Aleknavicius et al., 2022; Ververis et al., 2022). Some spore-forming bacteria can, however, re-occur after processing (SLU et al., 2018).

Some crickets contain cyanogenic glycosides derived from plants and the consumption of such crickets may cause acute poisoning that can cause damage to the central nervous system and retard growth (Islamiyat et al., 2016; Magara et al., 2021; Zagrobelny et al., 2009). Allergic reactions may occur in individuals sensitive to insect chitin following the consumption of crickets (EFSA Scientific Committee, 2015). In addition, the consumption of crickets without removing the legs may result in intestinal blockage, while the tough exoskeleton found in some crickets may be indigestible by humans (Magara et al., 2021).

8 Regulation relating to edible crickets

Legislation on the use of edible insects across the world remains limited; however, some countries have legislation that approves the breeding of certain cricket species (Mariod, 2020). The production of *A. domesticus*, *G. sigillatus* and *G. assimilis* for use in fish feed is approved in the EU (Commission Regulation (EU), 2017). In 2017 the Thailand National Bureau of Agricultural Commodity and Food Standards (within the Ministry of Agriculture and Cooperatives) launched the Thai agricultural standards on Good Agricultural Practices (GAP) for Cricket Farming (TAS 8202-2017), which provides guidelines for safe cricket rearing (ACFS, 2017). *A. domesticus* produced in closed farming systems are considered safe by the EFSA panel and can be used as ingredients in several food products and snacks (EFSA Panel on Nutrition et al., 2021). In addition, some African countries, such as Botswana, Kenya, Uganda, Tanzania and Malawi, have policies that identify insects as food and feed (Niassy et al., 2022).

9 Conclusion

The occurrence of various species of edible crickets offers a diversified nutrient-dense food and feed source that is easy to produce and can supplement existing protein sources to enhance food security. The existing and expanding demand for such a valuable resource has spurred small scale cricket production in Asia and Africa and large scale automated production in western countries; culminating into circulation of high value market products. However, global cricket production remains low and concerted efforts towards intensified production has been curtailed by inadequate policies and regulations, safety concerns and insect diseases that can wipe out commercial cricket colonies. Thus, there is need for optimization of cricket production to increase productivity, limit safety concerns and minimize disease occurrence. There is also need for development of national and international policy frameworks to enhance the production and trade of crickets as food and feed globally.

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