Kusia *et al. CABI Agriculture and Bioscience* (2023) 4:43
https://doi.org/10.1186/s43170-023-00186-y

CABI Agriculture and Bioscience

REVIEW

Open Access

A review of edible saturniidae (Lepidoptera) caterpillars in Africa

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Abstract

Background Edible saturniids constitute an important component of traditional diets in sub-Saharan Africa. They are also a source of livelihood for many rural communities both as food and as a source of income.

Main body This review compiles information on the diversity, distribution, decimating factors, nutrition and conservation concerns of edible saturniids. A compilation of nutritional profiles, amino-acids, mineral and fat content of saturniids is presented. Details of edible saturniids consumption and food plants are listed as well as vernacular names in different parts of Africa. A comparison of collection, processing, storage and trading methods based on available literature is also included. Processing, which is mostly carried out by women, involves tedious and time-consuming methods that need to be improved. Poor handling and storage cause bacterial and fungal contamination that raises food safety concerns. An in-depth discussion of conservation concerns and possible interventions is also provided.

Conclusion We conclude that edible saturniids are a source of highly nutritious food and incomes to many households in SSA, but wild harvesting is increasingly becoming unsustainable. We also conclude that the seasonal nature of availability limits their potential for profitable trade Further research on rearing edible saturniids is required since wild harvesting is unsustainable. Training women and youth on mass production technologies will ensure continuous supply of the insects and help preserve their natural habitats.

Keywords Saturniids, Edible caterpillars, Insect consumption, Entomophagy, Host plants

Background

Food security is currently one of the major challenges in the developing world. The world population is expected to cross the 9 billion by the year 2050 resulting in a substantial increase in food demand (Grafton et al. 2015). There are about 820 million people suffering from hunger globally of which 256 million live in Africa (FAO 2019). Apart from hunger, people also suffer from poor nutrition. Inadequate protein supply in developing countries is one of the causes of malnutrition (Ghosh et al. 2012). To meet the increased food demand, agricultural production will have to double by the year 2050 (FAO 2050). Currently, agriculture occupies 30% of earths land and increasing this proportion will conflict with other land uses. About 70% of the global agricultural land is utilized for livestock production especially for feed crop production (Steifeld et al. 2006). Increasing livestock production to nourish the growing population will require more agricultural land which is unsustainable as clearing more land will have huge detrimental effects on biodiversity and further accelerate climate change (Foley et al. 2005). Increasing livestock production also increases demand on water. Currently, 70% of fresh water is used for crop production, including fodder for the livestock sector (Doreau et al. 2012). In addition, CO_2 equivalents amounting to 18% of total anthropogenic greenhouse

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gases (GHG) and 64% of anthropogenic ammonia emissions are associated with livestock production (5). Hence the need to explore alternative protein sources, such as edible insects that can be used as both human food and animal feed (Belluco et al. 2017; Chia et al. 2019; Dobermann et al. 2017; Henry et al. 2015; Kelemu et al. 2015; Makkar et al. 2014; Huis et al. 2013). In addition to being highly nutritious (Charlotte et al. 2015; Mattia et al. 2019; Raphael Kwiri et al. 2015), edible insect production requires much less land and water and emits less ammonia and GHGs (Oonincx et al. 2010; Oonincx and Boer 2012), compared to other animal protein sources like fish, poultry and livestock.

Entomophagy (the consumption of insects) is traditionally practiced by 3071 ethnic communities spread out in 130 countries across the globe (Ramos-Elorduy 2009). About 2100 species are consumed worldwide by over 2 billion people (Jongema 2017). More than 500 species of edible insects have been recorded in Africa (Kelemu et al. 2015). Insects belonging to three orders namely Lepidoptera, Orthoptera, and Coleoptera are the most popular (Kelemu et al. 2015; Huis 2003). Lepidopteran insects belonging to 396 species from 36 families alone constitute 18.3% of the total edible insect species consumed by humans worldwide (Shockley and Dossey 2014). In Africa, Lepidoptera constitute 60% of all edible insects consumed (Kelemu et al. 2015; Huis 2003). Among Lepidoptera, saturniid caterpillars with 109 species rank first and constitute 27.5% of edible caterpillars consumed. Edible saturniids mostly belong to the sub-family Saturniinae (Mabossy-Mobouna et al. 2016) but this review focuses on all edible Saturniidae in Africa.

A compilation of nutritional profiles, amino-acids, mineral and fat content of saturniids is presented. Details of edible saturniids consumption and host plants are listed as well as ethnic names used for them in different parts of Africa. A comparison of collection, processing, storage and trading methods adopted by various communities is also included. An in-depth discussion on conservation concerns and possible interventions is also provided.

Methods

A comprehensive compilation of literature on edible saturniids and their nutritional composition in Africa was established via searches on Web of Science, Medline and Google Scholar spanning the period from 2000 to 2023. The initial search using the key words "edible insects" generated 43,100 hits. Then the literature search was narrowed down to using the following search entry word combinations: (Genus and/or species name) AND ((edible OR edible insect OR entomophagy OR food OR feed) AND (nutrition* OR protein* OR fat* OR mineral* OR Amino acid*)). To illustrate the distribution, conservation concerns and host plants of edible saturniids we searched for: (Genus and/or species name) AND (food plant OR host plant OR distribution OR habitat). For parasitoids and pathogens, search strings were: (Genus and/or species name) AND (parasitoid OR bacteria OR fungi OR entomopathogen OR food safety); while for collection, processing and trade, we used: (Genus and/or species name) AND (collection OR processing OR storage OR trade OR commercialization). Cross referencing approach was used to find other publications.

The inclusion criteria were as follows: (i) Publication in peer reviewed journal. (ii) Articles had to be relevant to the genus and/or species of edible saturniids, as specified in the search entry. iii)Articles needed to contain information related to the nutritional composition of edible saturniids in Africa. This includes details on protein content, fat content, mineral composition, amino acids, or any other nutritional aspects. (iv) For articles related to the distribution, conservation concerns, and host plants of edible saturniids, the inclusion criteria involved relevance to the genus and/or species of saturniids and keywords related to food plants, host plants, distribution, or habitat. (v) Articles pertaining to parasitoids, bacteria, fungi, entomopathogens, or food safety concerning edible saturniids had to be relevant to the genus and/or species of saturniids and include keywords related to these topics. (vi) Articles related to the collection, processing, storage, trade, or commercialization of edible saturniids had to be relevant to the genus and/or species of saturniids and include keywords related to these aspects.

The exclusion criteria were as follows: project documents and papers that did not discuss edible insects. The final analysis included 92 publications.

Means of nutritional components were calculated from values extracted from the available literature, tabulated, and utilized to generate graphs. All values for nutritional components were recorded on dry matter basis.

Synthesis and discussion

Diversity and distribution of edible saturniidae in Africa

Different species of edible saturniids are found in different parts of Africa. Although the seasons vary between regions, availability of the caterpillars depend on the weather (Ande and Fasoranti 1997). They start to appear during the rainy season when trees have enough foliage for them to feed on. African saturniids have different host plants which mostly include forest trees, shrubs and some domesticated fruit trees (Agbidye and Nongo 2012; Anvo et al. 2016; Latham 2015; Thomas 2013; Nsevolo et al. 2023).

For example, the Mopane worm *Gonimbrasia belina* Westwood is mostly found in southern Africa including Zambia, Zimbabwe, Malawi, Namibia, Angola, Botswana and South Africa (Raphael Kwiri et al. 2015; Thomas 2013; Allotey et al. 1996; Ditlhogo 1996; Gondo et al. 2010). The insect is widespread in areas where the main food plant, the mopane tree *Colophospermum mopane* (Kirk ex Benth.) Kirk ex J.Léonard (Fabaceae) occurs in forestland that cuts across southern Africa (Allotey et al. 1996). However, the mopane worm also feeds on other plant species (Additional file 1). *Gonimbrasia belina* is mostly bivoltine in Botswana, Zambia and South Africa with two generations per rainy season (Ditlhogo 1996; Gondo et al. 2010). It usually occurs from October/November to December/January for the first and between February/March and April/May for the second generation (Ditlhogo et al. 1996). Adult moths live for about five days and their fecundity varies depending on location and time of the year (Ditlhogo et al. 1996). The moths are nocturnal, with males only flying near midnight, and hide or remain stationary during the day (Oberprieler 1995). In the more arid areas of Namibia, *G. belina* is univoltine, occurring from February to April (Thomas 2013; Oberprieler 1995) and in Zimbabwe between November and January (Dube and Dube 2010). *Gonimbrasia zambesina* is also consumed in Kenya and mostly feeds on the mango tree (Kusia et al. 2021; Kusia et al. 2021).

Another popular saturniid is the shea tree caterpillar, *Cirina forda* Westwood. It can be found throughout sub-Saharan Africa (SSA) (Mabossy-Mobouna et al. 2016; Agbidye and Nongo 2012; Badanaro et al. 1849; Dwomoh et al. 2010; Pinhey 1956), and is the most economically important edible saturniid since it is consumed and traded in all the regions where it is found. In West Africa, *C. forda* feeds mainly on the shea tree *Vitellaria paradoxa* C.F.Gaertn. (Sapotaceae) (Ande and Fasoranti 1997; Dwomoh et al. 2010; Odebiyi et al. 2011), while in the Democratic Republic of Congo (DRC) it prefers *Crossopteryx febrifuga* (Afzel. ex G.Don) Benth. (*Rubiaceae*) (Latham 2015) though its host plant range is even wider host plant (Additional file 1). For instance, it also feeds on the wild syringa, *Burkea africana* Hook. (Fabaceae) in Zimbabwe (Kozanayi and Frost 2002) and both on the ordeal tree *Erythrophleum suaveolens* (Guill. & Perr.) Brenan (Fabaceae) and the African pearwood *Baillonella toxisperma* Pierre (Sapotaceae) in Cameroon (Ngute et al. 2020). *Cirina forda* is univoltine in Nigeria with the larval appearance coinciding with the rainy season between July and September (Ande and Fasoranti 1997; Badanaro et al. 1849). However, it is bivoltine in DRC, where the larvae occur between November and January and October to May during the rainy season (Latham 2015; Balinga et al. 2004). In Cameroon, *C. forda* and *Gonimbrasia epimethea* Drury occur in June–September, while *Bunaea alcinoe* Stoll, *G. alopia* Westwood, *G. obscura* Butler and *G. oyemensis* Rougeot in June to August (Ngute et al. 2020).

Another edible saturniid in the south Sudanian zone of Burkina Faso is *C. butyrospermi* Vuillot (Séré et al. 2018; Payne et al. 2020a, 2020b; Cox et al. 2020) that solely feeds on *V. paradoxa*. Several saturniid caterpillars feed on the same host plant. For instance, in DRC, *C. forda*, *Lobobunaea phaedusa* Drury and *B. alcinoe* feed on *C. febrifuga*, and the auri tree *Acacia auriculiformis* A.Cunn ex Benth. (Fabaceae) is also a food plant for *G. epimethea, B. alcinoe, G. oyemensis, G. eblis* Strecker, and *G. obscura*. Locals in DRC plant auri trees in their homesteads and raise saturniid larvae from the forest on them for later consumption. Trees that host multiple saturniids are especially useful for farming edible saturniids (Latham 2015).

Lists of edible saturniids in Africa and their host plants have been compiled (Jongema 2017; Latham 2015). However, it is important to note that there has been taxonomic confusion in identification and naming some species. Cirina is sometimes confused with the genus Imbrasia. *Cirina forda* has been published under the name of *Bunaeopsis aurantiaca* while the caterpillar of *Imbrasia obscura* is often confused with the caterpillar of *Gonimbrasia hecate* and *Imbrasia jamesoni* (Mabossy-Mobouna et al. 2022).

Factors affecting saturniid populations

Edible saturniid populations vary greatly year to year due to different factors (Latham 2015). Especially natural enemies like predators, parasitoids and entomopathogens can seriously affect their populations. Parasitoids attack saturniids either at the egg, larval or pupal stage. More than 300 parasitoid species belonging to the families of Braconidae, Tachinidae, Pyralidae, Ichneumonidae, Sarcophagidae, Chalcidoidea and Proctotrupoidea (Peigler 1994) have been recorded. For example, *C. forda* pupae are attacked by the Chalcididae *Hockeria crassa* (Walker), *Megaselia scalaris* (Loew) and *Hockeria* spp. (Dwomoh et al. 2004; Muhammad and Ande 2014). *Hockeria* spp. have also been recorded as pupal parasitoids of *G. belina*. *Ceromya luteicornis* (Mesnil) attacks *G. epimethea* and *B. alcinoe* pupae. *Bunaea alcinoe* is also attacked by tachinid *Carcelia* spp., chalcid *Eucepsis* spp. and sarcophagid *Sarcophaga* spp. (Akanbi 1973).

Most larval parasitoids of saturniids are braconids. For instance, *Glyptapanteles maculitarsis* (Cameron) has been recorded from larvae of *G. zambesina*, *B. alcinoe*, *G. maja* (Geertsema 1975; Van Den Berg 1971; Walker et al. 1990) and *G. epimethea* (Latham 2015). The eupelmids *Mesocomys pulchriceps* (Cam.) *Eupelmus urozonus* (Dal.) and *Anastatus* spp., and the eulophid *Pediobius* sp. emerged from *G. belina* eggs in South Africa (Van Den

Berg 1971, 1974). In Nigeria *C. forda* eggs were parasitized by the eupelmid *Anastatus* spp. and the eulophid *Entedon* spp. (Odebiyi et al. 2011; Muhammad and Ande 2014).

In addition to parasitoids, several fungal species have been isolated from *C. forda* in Nigeria, including *Aspergillus niger, A. flavus, Trichoderma* spp. *Fusarium solani*, and *Beauveria bassiana* (Odebiyi et al. 2011; Muhammad and Ande 2014) as well as viruses like Granuloviruses (GV) and Nuclear polyhedrosis virus (Muhammad and Ande 2014). Finally, also birds and ants have been observed predating on edible saturniid caterpillars (Latham 2015).

Consumption of edible saturniids

Edible saturniid caterpillars are nutrient rich and hence form an important part of the diet for many people in SSA. The most popular species include *B. alcinoe, C. forda, C. butyrospermi, G. belina, G. epimethea* and *G. maja*. Most species are consumed in Congo and DRC (Additional file 1). While *G. belina* and *G. maja* are mainly eaten in southern Africa (Kozanayi and Frost 2002; Glew et al. 1999; Kwiri et al. 2020; Mbata and Chidumayo 2003; Obopile and Seeletso 2013), *C. butyrospermi* is more popular in West Africa (Anvo et al. 2016; Payne et al. 2020a; Cox et al. 2020; Ehounou et al. 2018), and *C. forda* is consumed throughout SSA (Mabossy-Mobouna et al. 2016; Latham 2015; Badanaro et al. 1849; Ngute et al. 2020; Obopile and Seeletso 2013; Thomas and Olatunji 2020).

In Nigeria, popular edible saturniids are larvae of *B. alcinoe* and *C. forda*, consumed mainly in Kwara, Benue and Niger states by the Igbo, Nupe and Yoruba people (Amadi et al. 2005; Braide et al. 2010; Fasoranti and Ajiboye 1993). Despite a decline in entomophagy among the youth in Botswana, the mopane caterpillar remains highly sought-after compared to other edible insects (Obopile and Seeletso 2013; Nonaka 1996). A recent study in Côte d'Ivoire found *G. oyemensis* and *C. forda* as the most consumed and traded insect species in Abidjan (Ehounou et al. 2018), and *C. butyrospermi* is popular in the Sudanian zone of Burkina Faso (Séré et al. 2018).

In many communities the consumption of edible saturniids plays an important role in their culture. This is evidenced by local communities naming saturniid species in their ethnic languages and their ability to differentiate between species (Mabossy-Mobouna et al. 2016) comprehensively documented the names of edible caterpillars in Congo.For example, *B. alcinoe* is called '*Igu*' by the Igbo people in eastern Nigeria and *C. forda* is called '*Kanni*' or '*Munimuni*' by the Yorubas in the west of the country (Amadi et al. 2005; Temitope et al. 2014). In southern Zimbabwe, the term mopane worm is used to refer to larvae of several saturniid species. They include *G. belina*, locally known as '*Macimbi*', *G. maja* and *C. forda* ('*Harati*') named after their host plant, *B. africana* which is called '*Mukarati*' in the Shona language (Kozanayi and Frost 2002). In the Setswana language, widely spoken throughout southern Africa, *G. belina*, *B. alcinoe* and *C. forda* are referred to as '*Phane*', '*Phata*' and '*Nato*', respectively (Obopile and Seeletso 2013).

While some communities like the Teke community in Congo refer to several saturniid species with one name (here *B. alcinoe, G. alopia* and *G. eblis* are addressed as '*Inkele*'), other communities in Congo such as the Baaka, Bomitaba, Kaka, Bodongo, Bonguili, Mbonjo and Yasswa all refer to *G. oyemensis* by the term '*Mboyo*' (Additional file 1).

Collection and processing edible saturniids

Harvesting, processing and storage of edible saturniids varies across SSA. The tedious harvesting and processing are usually carried out by women and children. In Namibia, they constitute 85% of the harvesters. Occurrence of mopane worms coincide with the rainy season, hence the need for division of labour in the household with some members harvesting caterpillars while others till the land (Thomas 2013). In contrast, men, women and children collect *C. forda* in equal measure in Togo, with the harvesting time coinciding with the school holidays, allowing the children to accompany their parents in the collection (Badanaro et al. 1849). As much as all community members keep an eye on the caterpillar season, children are the main insect collectors in the Bas Congo province of DRC. There, locals also carry the young caterpillars to their homesteads and place them on trees to mature (Latham 2015). The San in the Kalahari Desert in Botswana set camp in the forest whenever the caterpillars are in season (Nonaka 1996).

Caterpillars are collected by hand, either directly from the trees or from the ground while they climb down to pupate in the soil (43,61). In Nigeria, locals sometimes also dig the ground for prepupa that have burrowed to pupate. Moreover, they build pitfall traps around the base of the tree to trap the larvae prior to pupation (Agbidye and Nongo 2012; Fasoranti and Ajiboye 1993; Agbidye et al. 2009; Akanbi 2002).

After harvesting, the gut contents are removed by holding the caterpillar between the thumb and index finger and squeezing the contents out through the rear end. This is done to every caterpillar individually, hence time consuming. However, when fully grown and ready for pupation, there is no need to squeeze the guts since bodies are filled with a highly nutritive yellow substance instead of plant material. In some cases, the caterpillars are starved for 1–2 days to empty the gut contents

(Agbidye and Nongo 2012; Latham 2015; Thomas 2013; Kozanayi and Frost 2002; Mbata and Chidumayo 2003; Nonaka 1996; Akanbi 2002). The squeezing process discolours and pricks the hands, and fingers of the handlers which can sometimes cause bleeding. In southern Zimbabwe, processors who can afford buy gloves while others cover their fingers with tree barks for protection. Some people use bottles to squeeze out the gut from several insects at once but the downside is that bottles exert too much pressure expelling the yellow substance preferred by consumers (Thomas 2013; Kozanayi and Frost 2002). Hence more effective, less laborious and less time-consuming processing methods that at the same time ensure the safety of the processors and retains the quality of the insects are needed.

In Nigeria, after gut cleaning, caterpillars are boiled and sun- dried and then they are ready for transport, storage and sale or direct consumption in households. For the latter, dried caterpillars are often fried in onions, pepper and salt, turning them into a delicious stew, often accompanied by cassava or other sources of carbohydrates (Fasoranti and Ajiboye 1993; Temitope et al. 2014; Agbidye et al. 2009; Akanbi 2002). In addition, caterpillars in Namibia are often also roasted on charcoal (Thomas 2013). In Botswana (Obopile and Seeletso 2013 Dec 1; Nonaka 1996) and in Zambia (Mbata and Chidumayo 2003), they are roasted in hot ash and sand before sun drying.

In Zimbabwe, saturniid larvae are roasted on charcoal or cooked to facilitate removal of the spines; thereafter caterpillars are sun-dried. Alternatively, they can also be salted and sun-dried or boiled and then sun-dried. However, mopane worms processed in this way fetch lower prices in the markets since they still have the spines on. Moreover, salted worms have a whitish appearance not preferred by urban consumers and they are usually sold at markets in rural regions (Kozanayi and Frost 2002).

In the Bas Congo province of DRC, caterpillars are boiled in salted water with hot peppers, or in peanut butter, cassava leaves, or pumpkin and sesame seeds. When harvested in plenty, saturniid caterpillars are smoked and packed in sacks for later use or for sale in nearby markets (Latham 2015). Although smoking allows for a longer shelf life (> 3 months) compared to sun drying and boiling, the nutritional value of smoked and sun-dried caterpillars appears to be lower than fresh ones (Balinga et al. 2004; Rumpold and Schlüter 2013).

Trading edible saturniids

Marketing of edible saturniid caterpillars is an important source of income for many households in SSA (Kozanayi and Frost 2002; Agbidye et al. 2009; Baiyegunhi and Oppong 2016; Moruakgomo 1996; Yapo et al. 2017; Mavinkal Ravindran et al. 2022). However, owing to their seasonality, traders and vendors do not rely solely on these insects for income but are also involved in farming and trading of other food commodities (Ngute et al. 2020; Balinga et al. 2004).

Some traders buy caterpillars in bulk for sale in urban cities or for cross-border trade (Thomas 2013; Obopile and Seeletso 2013). For instance, in Zimbabwe, mopane worms are packed in sacks or large tins and sold to traders who repackage them into smaller quantities for resale on local markets. There they are either repackaged in plastic bags or wrapped in old newspapers. In some cases, bulk traders blend high quality and low-quality worms to fetch a better price (Kozanayi and Frost 2002). The most traded saturniid in this region is clearly *G. belina,* though other species like *G. maja, C. forda* and *G. ertli* are also available but they are comparatively less popular. Again, traders often mix the less popular, and by consequence also less expensive, species with *G. belina* caterpillars since it is difficult to market them individually (Kozanayi and Frost 2002).

Several studies looked into the marketability of edible caterpillars in different parts of Africa. However, most value chains of edible saturniid caterpillars are still in their infancy. For instance, in Côte d'Ivoire, *C. forda* and *G. oyemensis* are collected by insect collectors in forests (both national and those in neighbouring countries), then sold to local traders, followed by wholesalers and eventually are marketed by retailers to rural and urban consumers, which can be lucrative. In 2018, a kilo of *C. butyrospermi* dried caterpillar was valued at 3.5 USD or a box of 750 g of *G. oyemensis* dried larvae at 6 USD on urban markets in Abidjan, and with average monthly income from sale of insects > 100 USD and profit margins of up to 69% for traders (Ehounou et al. 2018).

In Togo, while collection involves men, women and children, *C. forda* trade is almost entirely carried out by women. The trade chain involves, wholesalers, middlemen, and retailers, and because of their seasonality women sell the caterpillars alongside other commodities like grains and legumes (Badanaro et al. 1849).

In Zimbabwe, mopane worms are sold in both rural and urban areas, with women being involved in small scale retailing and vending. However, bulky cross-border transportation and wholesale is mainly dominated by men. The caterpillars can be found in markets, supermarkets, roadside stalls, bus terminals as well as hawked in beer halls as a snack. In supermarkets, they are well packed and labelled. Cross-border trade occurs mainly in South Africa, Zambia, Botswana and even in DRC (Kozanayi and Frost 2002).

The most traded saturniid caterpillars in Namibia are *G. belina* and *G. maja* which are generally referred to as

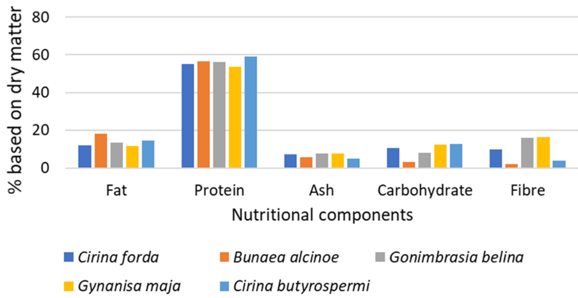

Fig. 1 Average nutrient content (based on dry matter) of edible saturniids from literature. Saturniids also contain all the essential amino acids (Fig. 2). The reported means of histidine, phenyalanine, tyrosine and threonine exceed the recommended daily allowance for adults (WHO 2007) for five edible saturniid species (Fig. 2). For *B. alcinoe,* amino acid contents exceed requirements for adults for all essential amino acids, while *C. forda* exceeded all except for histidine. No data could be retrieved on phenylalanine and tyrosine levels. Although amino acid levels for *G. maja* and *G. belina* larvae fall below the daily requirement for adults for isoleucine, leucine, lysine, methionine cysteine and valine, they still provide a substantial amount of amino acids (Fig. 2). Edible saturniids are also rich in non-essential amino acids (Additional file 1)

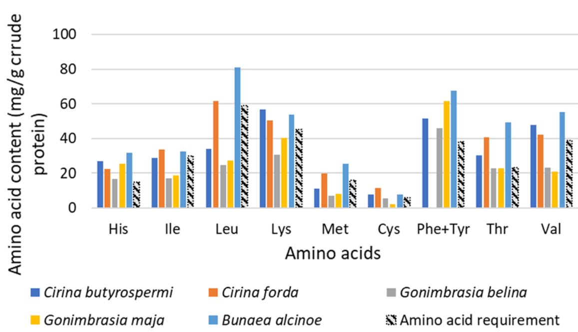

Fig. 2 Mean essential amino acid contents [mg/g crude protein] of edible saturniids from literature compared to amino acid requirements for adults (mg/g protein) (WHO 2007) *His* histidine, *Ile* isoleucine, *Leu* leucine, *Lys* lysine, *Met* methionine, *Cys* Cysteine, *Phe* phenylalanine, *Tyr* tyrosine, *Thr* threonine, *Val* valine. Edible saturniids are also rich in minerals, and *B. alcinoe* and *C. forda* are particularly high in phosphorus and potassium, while *G. belina* and *G. maja* are high in calcium and magnesium. However, except for *C. forda* this data is based on only one study (Additional file 1), highlighting the insufficient knowledge on the mineral content of edible saturniids in Africa

mopane worms. They play a crucial role in poverty alleviation for poor families, through trade, and providing food security, via direct consumption, for poor families. While harvesting is mostly carried out by women and children, unemployed males are often involved in the trade on urban markets. In Zimbabwe and Namibia, cross border trading of mopane worms to countries such as Angola is important (Thomas 2013).

Nutritional composition of edible saturniids

A literature comparison on the nutritional content of five saturniid species (*C. forda, B. alcinoe, G. belina, G. maja* and *C. butyrospermi*) showed that proteins account for the largest percentage of the proximate composition of edible saturniids. All five species have an average protein content > 50% (Fig. 1). The average fat content is > 10% with a range of 11.5–17.92% (Additional file 1). *Bunaea alcinoe* caterpillars have the highest fat content, and the ash content is ranging between 5% and 7.3% (Additional file 1). *Cirina forda* has the highest mean carbohydrate content (12.63%), while *B. alcinoe* has the lowest (3.16%), though the latter value is based on only one study (Agbidye et al. 2009*)*. Mean fibre content is highest for *G. maja* and *G. belina* and lowest in *B. alcinoe* (Fig. 1). All nutritional content studies for *C. forda* were carried out in West Africa with the saturniid feeding on shea trees (Badanaro et al. 1849; Agbidye et al. 2009; Igbabul et al. 2015; Omotoso 2006; Paiko et al. 2014). More studies are required to assess the effect of other host plants on the nutritional composition of *C. forda* larvae.

Food safety concerns

Edible saturniids are collected and processed in different ways depending on the region and community involved. Yet, these caterpillars may pose food safety concerns since they are harvested from the wild and hence it is difficult to set control measures. Traditionally, consumers use sight, taste and smell to determine whether the caterpillars are fresh. For instance, in Namibia, buyers either taste or watch out for mouldy caterpillars as a sign of poorly dried product (Thomas 2013).

Processing (degutting, boiling/roasting and sun-drying) is expected to remove toxins, reduce post-harvest losses and aid preparing of the insect in a more palatable form (Agbidye and Nongo 2012). However, poor storage and poor sanitation when handling edible saturniid caterpillars may lead to fungal and bacterial contaminations (Fig. 3).

Aspergillus spp. has featured prominently as a fungal contaminant of mopane worms sourced from different markets in southern Africa. Among the fungi isolated are *A flavus, A. parasiticus* and *A ochraceus* which are well known producers of aflatoxins and ochratoxins. In Zambia, high concentrations of aflatoxin were found in sampled *G. maja* and *G. zambesina* (Kachapulula et al. 2018). Other toxigenic fungi detected in edible saturniid caterpillars in Africa included *Penicillium* spp. and *Fusarium* spp. (Mpuchane et al. 1996; Simpanya et al. 2000). In market bought and field collected mopane worms, *Escherichia coli* and *Klebsiella pneumoniae* contamination were identified, and *Enterobacteriaceae* were still

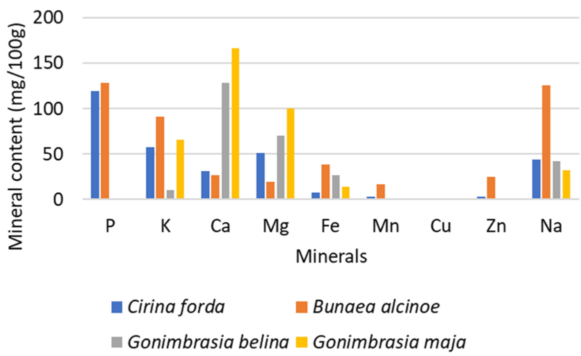

Fig. 3 Mean mineral contents [mg/100 g] of selected edible saturniids. Edible saturniids are to a varying degree rich in fats. For instance, linolenic acid (an essential fatty acid), stearic acid and palmitic acid are the most abundant fatty acids in *C. butyrospermi* (Anvo et al. 2016; Yapo et al. 2017). Oleic acid, stearic acid, and palmitic acid are the main fatty acids in *G. oyemensis* (Bi et al. 2015) while linolenic acid, stearic acid and oleic acids dominate the fatty acid profile of *C. forda* (Akinnawo and Ketiku 2000), and linolenic acid, palmitic acid and oleic acid are the most abundant in *G. belina* (Glew et al. 1999 Oct 1)

present after cooking the caterpillars, indicating faecal contamination (Gashe et al. 1997). In ash roasted mopane caterpillars *Staphylococcus aureus* was found (Mujuru et al. 2014), as were *Aspergillus* spp., *Penicillium* spp. and *Fusarium* spp. in roasted and sun-dried *B. alcinoe* larvae (Braide et al. 2011). In addition, bacteria including *E. coli*, *Pseudomonas aeruginosa*, *Proteus mirabilis* and *Streptococcus mitis* were also isolated from *B. alcinoe* samples (Braide et al. 2011).

In summary, poor sanitation during handling of edible saturniids combined with poor processing (delayed and uneven drying) and poor storage are the causes of bacterial and fungal contamination. Considering that edible saturniids are sold in open markets and as ready-to-eat snacks by street vendors, there is need to ensure improved hygiene practices during processing and handling of edible saturniids to reduce contamination.

Conservation concerns and interventions

Some of the major challenges affecting edible saturniids is over-harvesting and destruction of their natural habitats. Most saturniid host plants also have other uses including timber, firewood, fruit trees and medicinal uses (Ngute et al. 2020). Edible saturniids are most often harvested from the wild, underlining the importance to conserve their host plants.

Some African governments have started to put conservation measures in place. For instance, in Namibia there are restrictions on harvesting of mopane worms by giving permits to harvesters to curb over-exploitation. However, these permits do not specify the amounts and size of caterpillars that are allowed to be harvested (Thomas 2013), and in addition illegal harvesting of mopane worms is still widespread. Monitoring is poor and offenders are rarely punished (Thomas 2013). Establishing co-operative societies could be one strategy to better manage such resources (Thomas 2013). Presently, authorities in Namibia lack sufficient rules governing the management and utilization of mopane worms since the insects are considered of low economic value. Most of the Namibian mopane belt is located in communal areas where informal customary laws permit anyone to harvest. However, some communities have set up local regulations to curb mopane worm over-exploitation. For example, in the Uukwaluudhi area a traditional authority was set up which regulates harvesting of mopane worms, announcing the availability of mopane caterpillars via radio and community gatherings. Illegal cutting of the mopane tree for firewood or building is prohibited, and locals are also discouraged from setting fires in the forest and over-harvesting caterpillars since this would jeopardize the subsequent development of mopane populations (Thomas 2013). Apart from human interference, other factors like prolonged drought and floods adversely affect mopane populations (Thomas 2013).

Similarly, conservation concerns have been raised in Nigeria in relation to the shea tree caterpillar. Among the recommendations, forest conservation and establishing shea tree plantations to increase insect populations feature prominently. One of the interventions that is already yielding results is using pitfalls to harvest the caterpillars which prevents over-harvesting by avoiding breaking tree branches to reach caterpillars from the shea trees (Agbidye and Nongo 2012). The Tiv community in Nigeria have developed traditional conservation strategies for *C. forda* which include delaying cultivation around *V. paradoxa* trees until adult moths emerge to reduce disturbance of the pupae buried in the ground. They also allow a few larvae to pupate during harvesting by sparing some host trees to ensure future generations of the insect. Some people even stop cultivation completely around *V. paradoxa* trees that were previously infested by *C. forda* (Agbidye and Nongo 2012).

In Zambia, the Bisa community considers cutting trees that host edible caterpillars like *G. maja* and *G. belina* a taboo. However, population pressure and commercialization unfortunately weakened such rules with some locals ignoring informal rules and cutting tree branches to collect the caterpillars (Mbata and Chidumayo 2003). In Zimbabwe, caterpillar populations decrease in December to January prompting harvesters to collect the insects in premature stages which leads to over-harvesting negatively affecting the subsequent development of insect populations (Kozanayi and Frost 2002).

Traditionally, in the Bas Congo province of DRC, the first generation of *C. forda* is not harvested and caterpillars found high up on tree branches are spared. However, in many villages these safeguards are no longer adhered to. The other concern is burning bushes to clear land for cultivations and to repel rats; this kills the soil-dwelling saturniid pupae, hence greatly reducing caterpillar populations (Latham 2015).

Logging also adversely affects edible saturniid populations. Edible saturniids are categorised as non-timber forest products. Cutting down high value timber trees like *E. cylindricum* has led to a decrease in saturniid caterpillars, as these trees usually have a wider crown hence carrying sizeable caterpillar populations (Muvatsi et al. 2018). While edible saturniids are an important resource, it is difficult to safeguard them in regions where logging for timber is a major activity, mainly for economic reasons. A good example is Sapelli (*Entandrophragma cylindricum* Harms, Meliaceae) and Tali (*Erythropheum suaveolens* (Guill. & Perr.) Brenan, Fabaceae) trees in DRC that are important host plants for *G. oyemensis* and *C. forda*, respectively. Forest management there is often more geared towards safeguarding forests for logging and not necessarily for the sustainable harvesting of edible caterpillars (Muvatsi et al. 2018; Karsenty and Ferron 2017). Trees, especially those close to the forest borders where locals traditionally harvest caterpillars, should be safeguarded for harvesting while logging should be confined more to the inner parts of the forest.

Another example is the African pearwood *B. toxisperma*, a wild host plant of *C. forda* in Cameroon. Apart from being a class A timber species, the tree also produces fruits from which an edible oil is extracted. Efforts are in place to domesticate *B. toxisperma* and *E. cylindricum* since they are categorised as vulnerable under the IUCN RedList of threatened species. One conservation strategy is incorporating such tree species into agroforestry systems like cocoa plantations as shown with mango and the safou tree *Dacryodes edulis* H.J. Lam (Burseraceae) in Cameroon (Ngute et al. 2020).

Production of edible saturniid caterpillars

Since all the saturniid caterpillars consumed in Africa are harvested in the wild, it is necessary to delve into semi-domestication of the caterpillars (Yen 2015). However, edible saturniid caterpillars are not as easy to mass produce as crickets or mealworms because they usually need fresh leaves and many of them, such as the shea tree caterpillar, have an obligatory diapause that is not easy to break (Bama and b. et al.. 2018). Latham (Latham 2015) gives an example of a farmer who brought live *C. forda* larvae from the market and introduced them in a savanna area that had plenty of *C. febrifuga* trees. He was able to harvest caterpillars in the subsequent seasons and reported that avoiding fires in the area kept the insects there every year. Locals in the Bas Congo province of DRC have planted *A. auriculiformis* trees near their homesteads where they place young caterpillars collected in the forest to mature for consumption. They also leave some of the caterpillars to mature and pupate in their compounds. The moths that emerge often lay eggs within vicinity of the home vicinity and the insect population grows (Latham 2015). More work is required in creating awareness and training communities on such semi-wild production schemes of edible caterpillars to conserve the habitats and increase caterpillar yields.

Conclusions and recommendations for future work

Edible saturniids are a source of highly nutritious food and incomes to many households in SSA. However wild harvesting is increasingly becoming unsustainable. Their seasonal nature also limits their potential to profit the communities involved. Rearing methods need to be developed to ensure a more continuous supply and to help conserve their natural habitats. More research is also needed to develop better processing and storage methods that are faster, less tedious and improve food safety quality of the caterpillars. Development of insect-based food products should also be explored to process the caterpillars into more palatable forms with a longer shelf life. Gender mainstreaming should be considered when developing policies to sustainably maximize the benefits of edible saturniids in SSA. Value chains of edible saturniids need to be improved to establish possible points of intervention for maximum utilization of the food resource.

Policy recommendations aimed at promoting the sustainable utilization of edible saturniids in SSA while addressing the challenges associated with wild harvesting and seasonal availability are as follows:

i) Promote Sustainable Rearing Practices: Develop and implement policies that support the development of sustainable rearing methods for edible saturniids. This can include providing training and resources to local communities interested in rearing these insects. Encourage the establishment of community-based rearing programs to ensure a more continuous and reliable supply of edible saturniids.

ii) Conservation of Natural Habitats: Implement policies to conserve the natural habitats of edible saturniids, including forests and other ecosystems where they are found. Explore the designation of protected areas or conservation zones to safeguard these habitats.

iii) Research and Innovation: Allocate funding for research on improved processing and storage methods for edible saturniids that are efficient, hygienic, and suitable for local communities. Support research initiatives aimed at developing insect-based food products that are more palatable, have a longer shelf life, and cater to local tastes and preferences.
iv) Gender Mainstreaming: Integrate gender considerations into policy development and implementation to ensure that women, who are often involved in collecting and processing edible saturniids, have equal access to benefits and opportunities. Promote training and capacity-building programs for women involved in the edible saturniid value chain.
v) Value Chain Enhancement: Develop policies that enhance the entire value chain of edible saturniids, from harvesting and processing to marketing and distribution. Identify points of intervention to maximize the utilization of edible saturniids as a food resource, which may include creating market linkages and supporting local entrepreneurs.
vi) Education and Awareness: Implement awareness campaigns and educational programs to inform local communities about the nutritional benefits of edible saturniids and the importance of sustainable harvesting and rearing practices. Encourage schools and community organizations to incorporate information about edible saturniids into their curricula and outreach activities.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00186-y.

Additional file 1: Edible saturniids in Africa and their host plants. A tabulated list of edible saturniids in Africa and their respective host plants. Local names of edible saturniids in Africa. A tabulated list of local names of edible saturniids in Africa. Nutrition composition (%) of selected edible saturniids (based on dry matter). A table showing Nutrition composition (%) of selected edible saturniids. Amino acid composition (mg/g) of selected edible saturniids (based on dry matter). A table showing Amino acid composition (mg/g) of selected edible saturniids. Mineral composition (mg/100 g) of selected edible saturniids (based on dry matter). A table showing mineral composition (mg/100 g) of selected edible saturniids.

Acknowledgements
Not applicable.

Author contributions
ESK: Conceptualization, methodology, formal analysis, writing-original draft. CB: Conceptualization, writing-review and editing, supervision, funding acquisition. SS: Conceptualization, writing-review and editing, supervision, funding acquisition, project management.

Funding
Open Access funding enabled and organized by Projekt DEAL. This study was funded by Federal Ministry for Economic Cooperation and Development (BMZ) (ENTONUTRI–81194993). The study was also supported by*icipecore funding provided by UK Aid from the Government of the United Kingdom; Swedish International Development Cooperation Agency (SIDA); the Swiss Agency for Development and Cooperation (SDC); Government of the Federal Democratic Republic of Ethiopia and the Kenyan Government.*

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no any conflict of interest.

Received: 5 June 2023 Accepted: 17 October 2023
Published online: 24 October 2023

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