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REVIEW ARTICLE

Edible Lepidoptera as human foods – a comprehensive review

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Abstract

As the global population continues to grow, traditional protein sources like meat and fish are becoming increasingly unsustainable due to their environmental impact. Edible insects, on the other hand, are highly nutritious, require minimal resources to produce, and emit significantly fewer greenhouse gases than traditional livestock. Lepidoptera, one of the most diverse insect orders, contains some popular edible species that have been consumed traditionally for centuries across the globe. Based on this review, about 24 families with a total of about 350 edible lepidopteran species were recorded. They are often praised for their excellent nutritional value, such as having high protein and healthy fat content. Edible lepidopterans also contain minerals, essential amino acids, and vitamins, making them a nutritious addition to a balanced diet. They also contain bioactive compounds which have various nutraceutical and pharmaceutical properties. Furthermore, some edible lepidopterans can be farmed and require minimal space and resources. However, there are significant challenges associated with their use as food. One of the primary challenges is the lack of regulations governing their production and distribution, which creates uncertainty for consumers and businesses alike. Consumer acceptance is also a significant barrier to the widespread adoption of insects as food. To overcome these challenges, there is a need for clear regulations that ensure the safety and quality of insect-based products. Furthermore, it is important to raise awareness about the nutritional and environmental benefits of edible insects as sustainable food for the future to promote their acceptance among consumers.

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Keywords

edible insects – nutritional value – regulations – consumer acceptance – sustainable food

1 Introduction

Edible insect species means "any insect that is appropriate or harmless to eat" and eating insects is known as entomophagy. Entomophagy is a prehistoric practice of eating insects as food, which keeps cultural features of continents include Asia, Africa, Australia, Latin America, and Oceania. All over the world presently, above two billion people consume inclusive variety of insects (Halloran *et al*., 2016; van Itterbeeck and van Huis, 2012). Furthermore, it has been a dietetic custom for centuries by several people from several cultures all through the world as a consistent part of their food intake (van Huis *et al*., 2021; Yen, 2015a).

It is predicted that world's growing population will go beyond 9 billion in 2050, and the falling of arable land, evolving and picking of extra food resources are necessary (van Huis *et al*., 2013). Regarding this issue the Food and Agriculture Organization (FAO) has predicted edible insects as one vital resolution to food insecurity (van Huis *et al*., 2013). Insects are considered as a possible maintainable food source for increasing world population and encourages the practice of entomophagy (Vantomme, 2015). The most eaten insects orders are given following: Coleoptera, 31% (beetles); Lepidoptera, 18% (caterpillars, butterflies, and moths); Hymenoptera, 14% (ants, bees, and wasps); Orthoptera, 13% (crickets, grasshoppers, and locusts); Hemiptera, 10% (cicadas, leafhoppers, planthoppers, scale insects, and true bugs); Blattodea, 3% (termites); Odonata, 3% (dragonflies); Diptera, 2% (flies) and others 5% (Avedaño *et al*., 2013; Hlongwane *et al*., 2020; Meyer-Rochow *et al*., 2021).

Insects are best substitute nutrient source that has great amount of essential nutrients for human and animal diets (Rumpold and Schlüter, 2013). Regarding nutritional point of view, insects are not lower than other sources of protein, like chicken, beef, and fish (Belluco *et al*., 2013). Similarly, production of insects is considered more maintainable as compared to livestock animals since insects have a great efficiency of food conversion, having exceptional potential to be upraised by using organic waste products, high productiveness, and short life cycle (Rumpold and Schlüter, 2013). They also need less water and space in the procedure of mass breeding as compared to other livestock animals (Baiano, 2020; Enwemiwe and Popoola, 2018; Musundire *et al*., 2021; Skotnicka *et al*., 2021). For instance, 1 gram of edible beef protein needs 8 to 14 times extra space and around 5 times extra water than mealworms (van Huis and Oonincx, 2017). Additionally, insects have high amount of antioxidants and are useful for the gut flora of humans (Babarinde *et al*., 2021; Raubenheimer and Rothman, 2013; Stull *et al*., 2018).

Insects can grow in controlled breeding environment with less emission of ammonia and greenhouse gas emissions, with no climatic disturbance (Müller *et al*., 2016). Except all these benefits, edible insects are still considered taboo in many western communities and human consumption of insects has feeling of unwillingness (Looy *et al*., 2014). Though this concept has started to change as FAO reassures entomophagy because of highly cost-effective prospect as best alternative of food security with less environmental effect (Perez Vazquez *et al*., 2018). It was observed that edible insects are mostly acceptable as typical Western food in processed form with unrecognizable texture and taste. Attaining a good quality food produce from insects and making it acceptable to consumers there should be proper laborious procedures for food sanitation, sterilization, and hygiene at each phase of the production method, to assure that the final edible insect product is nontoxic, healthy and completely sterilized (Caparros Megido *et al*., 2017).

Global Biodiversity Information Facility (GBIF) establishes Lepidoptera as one of the utmost significant orders regarding diversity and abundance, with above of 188,359 species refer to above of 4,000 genera (GBIF, 2020). There are more than 350 species of edible Lepidoptera are consumed worldwide (Costa-Neto, 2014; Turpin, 2013; Yen, 2015a). Life cycle of Lepidoptera consist of four different stages: firstly egg, second larva (caterpillar), third pupa (chrysalis), and finally adult (butterfly or moth). Most edible lepidopterans are consumed in their juvenile phases like larvae and pupae (Yen, 2012). Although it is specified that approximately 2,000 to 3,000 insect species consumed all over the world (Hanboonsong *et al*., 2013), the real number might be bigger than this, since the insects eaten by the native communities and traditional groups have not been thoroughly documented.

Among edible insects, edible caterpillars subsidize to food sanctuary as an outstanding source of proteins, carbohydrates, lipids, minerals, and vitamins. These are also helpful in economic growth of rural regions where they are collected and treated for sale in the market (Félix, 2019; Loh *et al.*, 2017; Meutchieye *et al.*, 2016; Ngute *et al.*, 2020). Bioavailability of edible caterpillars offers a source of contesting malnourishment in Africa and evading metabolic disorders (Mlcek *et al.*, 2014a; Moyo *et al.*, 2019). Since caterpillars have high nutritious value, they are mixed with flour to make porridge to compete with malnourishment in children, weak people, and expectant women (Nantanga and Amakali, 2020).

This review paper will give an updated information on consumption of edible Lepidoptera to overcome the global issue of food security. It will also give information about harvesting and breeding procedure of order Lepidoptera by applying feasible and economical ways.

2 List of edible Lepidoptera and records of their consumption in the world

Lepidopterans are the second most edible insects globally only after coleopterans (Okore *et al.*, 2014; van Huis *et al.*, 2013). Most of edible lepidopterans are consumed as larvae with few been consumed as pupae or adults (Supplementary Table S1). They are eaten either boiled, roasted, fried or even raw (Ishara *et al.*, 2022; Okore *et al.*, 2014). Some are dried or smoked for preservation. They may be eaten as snack, cooked in stew or as relish and in some cases, they may be eaten raw (Hlongwane, 2021; Baiano, 2020). In the indigenous sense, cooking method depends mostly on the tradition passed on from older generations (Hlongwane, 2021). The cooking method also largely depends on the stage of the insect as well as individual preference. For example, in Nigeria, Adeoye *et al.* (2014) reported that about 62% of the population interviewed prefer their insects roasted, followed by 28% who prefer fried insects and 7% prefer boiled insects. From our list, about 24 families with a total of about 350 edible lepidopteran species were recorded around the globe (Supplementary Table S1).

Edible lepidopterans were recorded across 6 continents including Africa, Asia, Europe, North America, South America, and Oceania. In most cases, the edible lepidopterans seem to be continent specific. Quiet few species are found across continents such as *Agrius convolvuli*, *Pectinophora gossypiella*, and *Ostinia furnacalis* that found in Asia and Africa.

Lepidopterans are said to be the most consumed insects in the Southern, Central and Western Africa serving as an important source of nutrients to households, as well as being a major source of income to the rural populace (Kelemu *et al.*, 2015). About 139 species of edible lepidopterans from 18 families are recorded in 35 African countries. Saturniidae seems to be the most preferred family across the continent, recording about 49% edible lepidopterans, followed by Notodontidae, 12% and Sphingidae, 8% (Figure 1). This is not different from the many records of edible lepidopterans across the continent (Ishara *et al.*, 2022; Lautenschlager *et al.*, 2017; Loh *et al.*, 2017; Kelemu *et al.*, 2015; Mabossy-Mobouna *et al.*, 2022; Muya *et al.*, 2022; Okore *et al.*, 2014; Ouaba *et al.*, 2022). In the D.R. Congo, Mabossy-Mobouna *et al.* (2022) recorded Saturniidae as the most represented family with 44.8% of species, followed by Notodontidae representing 34.5% of sampled edible lepidopterans. About 9 species among these edible lepidopterans are consumed quite widely across the continent, i.e. *Anaphe venata*, *Anaphe infracta*, *Bunaea alcinoe*, *Cirina butyrospermi*, *Cirina forda*, *Gonimbrasia belina*, *Imbrasia ertli*, *Imbrasia epimethea*, and *Urota sinope*. From our compiled list, the D.R. Congo recorded the highest number of edible lepidoptera, about 68 species, the Zambia, which recorded about 36 species. This can, however, not be very conclusive due to factors such as lack of literature or documented records from other countries, or due to lack of identification of some of the edible lepidopterans (Ishara *et al.*, 2022; Mabossy-Mobouna *et al.*, 2022; Okore *et al.*, 2014; Ouaba *et al.*, 2022).

From the total list compiled, about 108 species of edible lepidopterans in 24 families were recorded from 9 countries in Asia. Figure 2 shows that Hepialidae family recorded the most consumed edible lepidoptera species representing 36%, followed by Sphingidae with 13%, with the third most consumed being represented by Saturniidae and Lasiocampidae with 6% each. China records the highest number of edible lepidopterans in Asia with about 68 species, followed by Japan which records about 19 edible lepidopteran species (Jongema, 2017).

Records from North America were all from Mexico with 78 edible Lepidoptera species from 16 families. The most consumed species are from the family Saturniidae (26%), followed by Pieridae (17%), and Nymphalidae (15%) (Figure 3). Mexico recorded the highest species of edible lepidopterans. Edible lepidopterans recorded from South America were recorded from 5 countries.

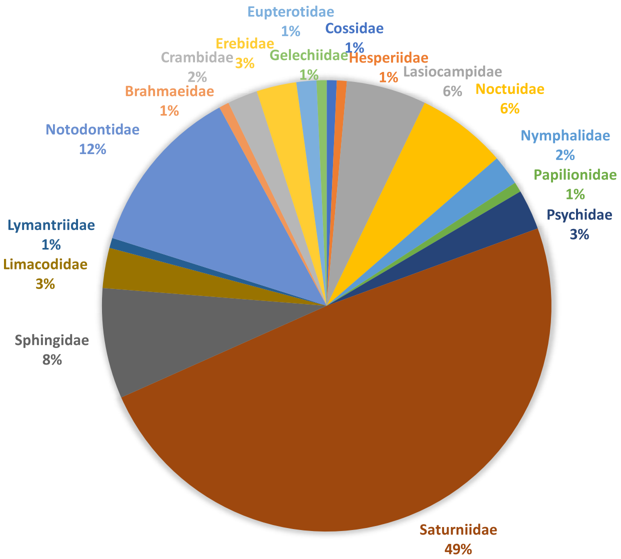

FIGURE 1 Families of edible lepidopterans of Africa.

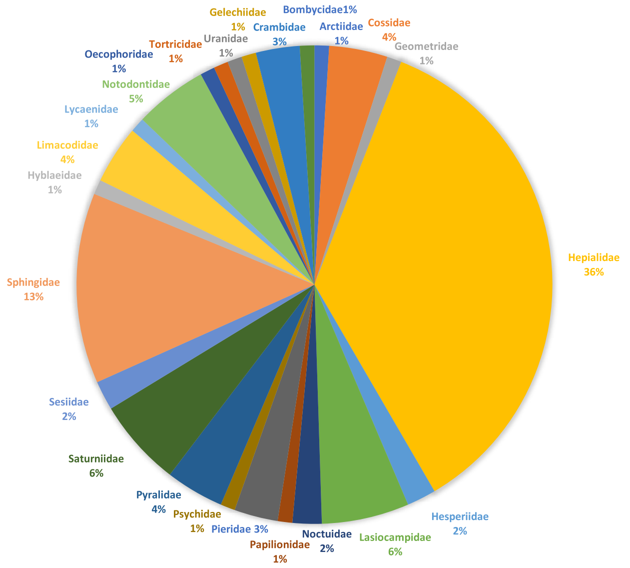

FIGURE 2 Families of edible lepidopterans of Asia.

About 23 species from 12 families, with Noctuidae representing the family with most consumed species, 4 (18%) (Figure 4).

In the Oceania region, 19 species of edible lepidopterans were recorded from 6 families in 3 countries. Australia recorded the highest number of edible Lepidoptera species (17) in the region. The highest number of species consumed are from the family Cossidae, 8 species representing 42% of edible lepidopterans in the continent (Figure 5). In Europe the only record found is from Italy with 2 edible lepidopterans from 2 families.

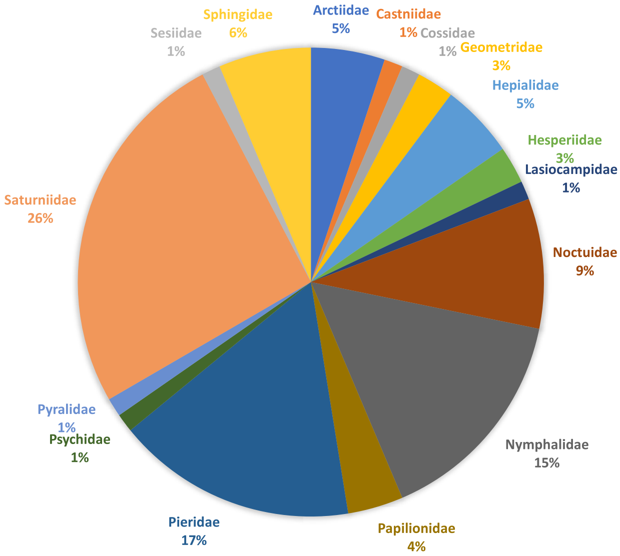

FIGURE 3 Families of edible lepidopterans of North America.

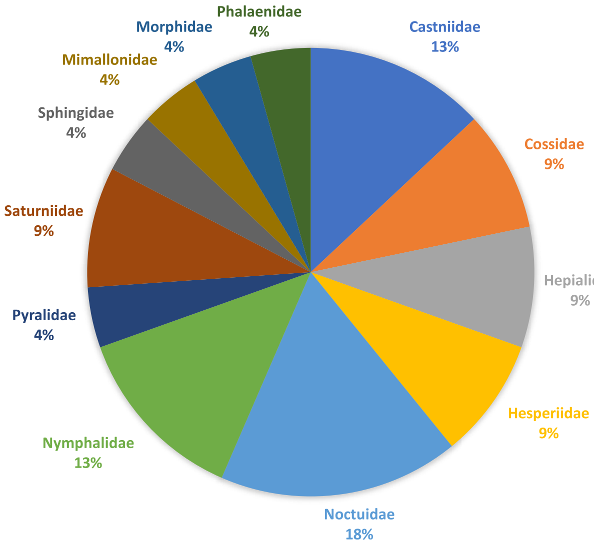

FIGURE 4 Families of edible lepidopterans of South America.

3 Bioecology of selected edible Lepidoptera species

There is limited published literature on the life cycle of tropical edible lepidopterans (Table 1). Life cycle duration of some of these edible lepidopterans differ based on seasonal variations; shorter in the dry season and longer in the rainy season (Mbahin *et al.*, 2012). *Aegocera rectilinea* for example has relatively short life cycle (≈43 days) making it one of the frequently available caterpillars for consumption (Muya *et al.*, 2022). The population dynamics of lepidopterans in the wild is directly dependent on the availability of their host plants which is also dependent on the climate, particularly rainfall (Lautenschlager *et al.*, 2017). Voltinism, the number of generations produced per year, is

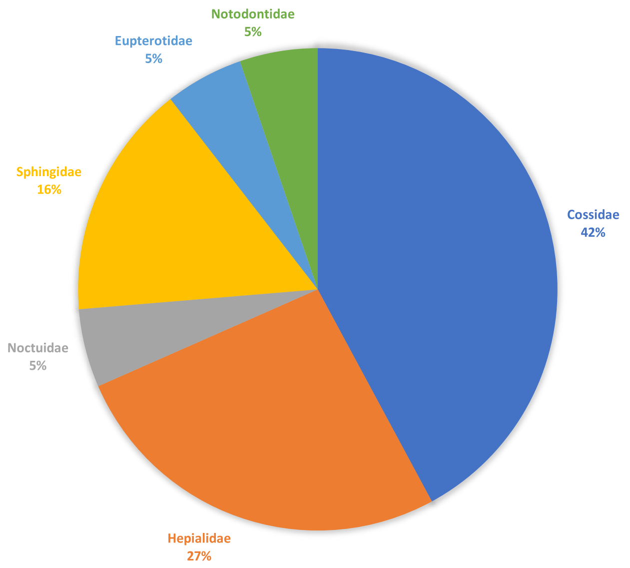

FIGURE 5 Families of edible lepidopterans of Oceania.

said to be dependent on abiotic factors such as photoperiod, temperature, and host plant availability (Bara *et al.*, 2022). Most species widely consumed in Africa are monovoltine (Muya *et al.*, 2022). Others such as *Bunaea* spp., *Gonimbrasia* spp., and*Gynanisia nigra* are bivoltine, while other such as *Samia ricini* are multivoltine (Kusia *et al.*, 2021; Wongsorn *et al.*, 2015). There is variation in the availability period of edible caterpillars from region-to-region probability based on varied climatic conditions (Kusia *et al.*, 2021; van Hui and Oonincx, 2017). Lautenschlager *et al.* (2017) observed that in Angola the main season for the edible caterpillars catalogued starts in January and lasts till February. They were however astonished recording of *Imbrasia dione* in July, which seem to be an out layer with regards to the caterpillar season in Angola. Edible caterpillars are available in the Central African Republic from mid-June to late September, from July to October in Cameroon and from August to January in Congo. In the D.R. In Congo, edible caterpillars are available at different times across the regions; from November to February in Bas-Congo, March to May in Katanga (Malaisse and Latham, 2014), July to September in Western Kasai, June to September in Kisangani and September to December in Bandundu region (Muya *et al.*, 2022). Mabossy-Mabouna *et al.* (2016) on the other hand also recorded the season for 3 regions: from mid-July to mid-August in Northern part, in the mid-October to mid-February in the central-southern part, and from mid-August to mid-September. This is usually dependent on availability of the host plants.

Some of edible lepidopterans are of importance in many other ways besides serving as food and feed for humans and animals. Some of these insects are pests of important crops causing various levels of economic damage to their host plants. The dilemma for farmers will be weather to control these pests immediately they appear on their fields to save their crops or to leave them till they mature for harvesting. The insects are harvested at various levels of their lifecycle. Caterpillars are mostly harvested at the final larval stage (Payne *et al.*, 2020) or even as pupa and adults. Some farmers may decide on a trade-off between the biomass of the insect and crop yield. This will mean harvesting the insects at a relatively younger stage to save their crops (Payne *et al.*, 2020). There may also be the decision of controlling the pests and saving the crops than waiting to harvest them for food, depending on which is more important to the farmer.

Cirina butyrospermi, the shea caterpillar is a pest of the shea tree from which shea butter is produced. They are usually harvested in the final larval stage before pupation by which time they would have caused extensive damage to their host (Payne *et al.*, 2020). The African armyworm, *Spodoptera exempta*, is a serious migratory pest of pasture and grains. Outbreaks are recorded yearly in Tanzania and sometimes even breakout to neighboring countries, causing devastating yield loss (FAO, 2021). The cotton bollworm, *Helicoverpa armigera*, is a global pest of crops, attacking over 200 plant species in about 20 families. Its management has mostly been insecticide and BT cotton dependent (Chen *et al.*, 2020), hence the use of this insect as food could be an interesting endeavor considering when to harvest the larvae to still ensure maximum crop yield. On another hand, the African wild silkmoth, *Anaphe* spp., are important for their wild silk production which is commercially exploited (Kebede *et al.*, 2014).

4 Nutritional value of selected edible Lepidoptera species

Edible lepidopterans are rich with essential nutrients for human body such as protein, fats, fiber, amino acid, fatty acid, vitamins, and minerals (Hlongwane *et al.*, 2020). In this review, these nutrients composition as reported in the body of literatures were presented. Overall, we managed to compile the nutritional value of more than 40 species of edible lepidopterans where most of these species were consumed by African and Asian people.

TABLE 1 Life cycle of selected edible lepidopterans with their host plants in Africa (Adopted from Badanaro *et al.*, 2014; Mbahin *et al.*, 2012; Muya *et al.*, 2022)

Species	Duration (days)			Life cycle (days)	Voltinism	Availability	Host plant
	Egg	Larva	Pupa				
Anaphe infracta	≈55	≈118	≈178	≈358	Monovoltine	August to September	*Bridelia micrantha*, *Pseudolachnostylis maprouneifolia*, *Cynometra alexandri*, *Triumfetta manrophylla*, and *Alhizzia fastigiata*
Aegocera rectilinear	≈3	≈20	≈12	≈43	Multivoltine	–	*Boerhavia diffusa*
Cirina forda	≈35	≈50	270	357	Monovoltine	July to September	*Albizia antunesiana*, *Euclea divinorum*, *Acacia mearnsii*, *Manilkara sulcata*, *Crosopteryx febrifuga*, *Vitellaria paradoxa*, *Burkea Africana*, and *Erythrophleum africanum*
Cirina butyrospermi	30	33	330	398	Monovoltine	June to August	*Vitellaria paradoxa*
Elaphrodes lactea	60	60	30	360	Monovoltine	December to January	*Millettia laurentii*, *Piptadeniatrum africanum*, and *Albizia ferruginea*
Gonimbrasia belina	10	42	210	265	Bivoltine	December to January April to May	*Anacardium occidentale* and *Colophospermum mopane*
Imbrasia obscura	–	–	–	–	Monovoltine	October to February	*Dichrostachys cinerea*, *Macaranga monandra*, and *Pentaclethra macrophylla*

Proximate value and energy analysis

The proximate and energy analysis of edible lepidopterans are shown in Supplementary Table S2. When compared, the 'soybean hawkmoth' or *Clanis bilineata* reported to has the highest amount of protein (92.5%) compared to the other lepidoptera species compiled. This species is widely distributed in China, Japan, India, and the Korean Peninsula (Zhao *et al.*, 2021). The larvae and pupae of *C. bilineata*are well known for their high nutritional value and considered as a safe source of protein (Gao *et al.*, 2021). On the other hand, Loh *et al.* (2017) reported that *Imbrasia dione* has approximately 10.87% of protein content; make it as the Lepidoptera species that has lowest protein content. Overall, 31 species of lepidopteran compiled in this review paper are reported to have more than 50% of protein content. The high protein content found in edible lepidopterans could help to combat protein deficiency especially in the poor countries. In fact, meat had a lower protein content than edible insects (Orkusz, 2021). Therefore, adding edible insects in daily diets might help reduce malnutrition rates in the society.

The crude fiber was reported to be highest in the 'thousand-headed snake' or *Latebraria amphipyrioides* with the amount of 29%. This moth is distributed in southern North America and Central America; and commonly consume by rural people in Mexico (Ramos-Elorduy, 2011). From the information gathered, edible lepidopterans are not a good source of fiber as 30 out of 40 species only have less than 10% of fiber with the lowest was reported in 'tebo worm' *Chilecomadia moorei*. Even though classified as edible, 'tebo worm' is not popular as human diet due to its low nutrient content and commonly sold as insectivores pet food and fishing bites (van Huis *et al.*, 2021).

Insects also have good dietary fats that essential for human to maintain a good health. Overall, the amount of fat in edible lepidopterans are range between 1.9% to 77%. Among all, *Phasus triangularis* has found to have the high amount of fat (77%) and the lowest was

Gonimbrasia alopia. The rich amount of fat in *P. triangularis* not only made it as valuable insect for human diet, but it also identified as a potential organism to be utilized for environmental-friendly biodiesel production (Manzano-Agugliaro *et al*., 2012).

The content of nitrogen-free extract (NFE) such as carbohydrates gives the value added for insect as part of human diet. Among all, *C. bilineata* was determined as having the highest amount of NFE compared to the other species (70.04%), while the lowest NFE content was recorded in the domestic silk moth *Bombyx mori* (Bombycidae) with 1% amount. The consumption of *Hemijana variegata* gives the best energy supply where 100 g of this insect can generate 23,119 Kcal of energy content. Even though *L. amphipyrioides* was determine as a good source of fiber, research shows that this moth species generate low amount of energy content (293 Kcal).

The amount of ash in edible lepidoptera was range from 0.63% to 30.3%. Meanwhile, the amount of moisture content was range from 92.4% to 1.31%. In this review, *Comadia redtenbacheri* was reported to has the lowest amount of ash and moisture content, while *C. bilineata* was found to has highest amount of those two components.

Mineral contents

Insects are rich with mineral contents such as calcium, potassium, sodium, chloride, phosphorus, and magnesium. They also also contain trace elements such as iron, copper, fluoride, selenium, zinc, chromium, molybdenum, iodine and manganese. In this review, we have compiled 10 types of essential mineral contents and compared the amount of those minerals among 24 Lepidoptera species (Supplementary Table S3). *Gynanisa maja* had the highest calcium (1664 mg/100 g) and magnesium (1000 mg/100 g) content. On the other hand, *C. bilineata* had the lowest calcium (0.57 mg/100 g) and *Anaphe infracta* had the lowest magnesium content (1.01 mg/100 g). Potassium was highest in *Aegiala hesperiasis* (6649.5 mg/100 g) and lowest in *Samia ricinii* (0.012 mg/100 g). The highest phosphorus was recorded in *B. mori* (1369.94 mg/100 g) and the lowest in *C. redtenbacheri* (0.33 mg/100 g). Sodium was recorded highest in *Usta terpsichore* (3340 mg/100 g) and lowest in *I. dione* (0.45 mg/100 g). Iron content was the highest in *C. forda* (64 mg/100 g), while *A. hesperiasis* had the lowest iron content (0.5 mg/100 g). Despite of its low calcium content, *C. bilineata* had the high amount of zinc (299.31 mg/100 g), while *Imbrasia oyemensis* only had 2.62 mg/100 g of zinc. *Anaphe venata* had 40.00 mg/100 g mangan which is the highest between species and the lowest was its sibling of same genus *A. infracta* (0.07 mg/100 g). Both *A. hesperiasis* and *C. redtenbacheri* had the highest amount of copper (11.4 mg/100 g), while the lowest was *C. forda*.

Amino acid and fatty acid

Edible Lepidoptera are reported rich with amino acid (Supplementary Table S4) and fatty acid (Supplementary Table S5) required by human body. Human needs 20 types of amino acids to function efficiently. However, only 9 are classified as essential which are histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Both amino acids and fatty acids are important to boost the human body biological activities such as to influence cell and tissue metabolism, function, and responsiveness to hormonal and other body signals. Köhler *et al.* (2019) reported only the silkworm met the FAO/WHO requirements of 40% essential amino acids and 0.6 ratio of essential to non-essential amino acids.

Vitamin

Supplementary Table S6 shows the amount of vitamin composition extracted from edible lepidopterans. Most of them had low number of vitamins and does not meet the minimum requirement per day intake as suggested by FAO/WHO. Vitamins play an important role in human nutrition, as Vitamin C is important for human growth, development, and repair of various body tissues. The excellent source of Vitamins found in some edible insects shows that insects have a great potential of being used as a healthy food supplement for malnourished people, or to prevent malnutrition.

5 Nutraceutical and pharmaceutical properties of edible Lepidoptera species

Research shows that the consumption of insect protein has potential advantages for human health. Insect protein could be used as a nutraceutical food ingredient in functional foods and dietary supplements designed to treat specific health conditions, such as obesity, diabetes, and cardiovascular disease (Siddiqui *et al.*, 2023). As an example, in the study by Skotnicka *et al.* (2022), the usage of insect-based food products was found considerably increased the food satiety. This finding shows the potential of insect protein for body weight management, especially to treat obesity. On the other hand, Rivero-Pino *et al.* (2021) reported that the protein of

TABLE 2 Biological activity of edible lepidoptera extracts

Species	Biological activity	Reference
Antheraea assamensis	Anti-tyrosinase activity	Deori *et al.* (2014)
Bombyx mori	Antigenotoxic activity Antioxidant activity Hypoglycaemic activity	Chao and Zhang (2016)
Chrysirida madagascariensis	Anti-sickling activity	Kalonda *et al.* (2015)
Clanis bilineata	Hypolipidemic activity	Xia *et al.* (2013)
Galleria mellonella	Anti-microbial	Lee *et al.* (2021)
Phylloxiphia vicina	PL inhibitory activity	Zhang *et al.* (2022)
Spodoptera littoralis	Anti-hypertensive	Lee *et al.* (2021)
Cinabra hyperbius, *Cirina forda*, *Gonimbrasia belina*, and *Imbrasia truncata*	Antioxidant activity	Kapepula *et al.* (2022)

yellow mealworms (*Tenebrio molitor*) could be used as ingredients for regulation of the glycaemic index which important for blood sugar control. Stul *et al.* (2018) stated that incorporating cricket protein into human diet has been shown to enhance the growth of probiotic bacterium *Bifidobacterium animalis*. This gut microbiota is good to improve the human gut health (Jordan *et al.*, 2021). In addition to that, the consumption of cricket protein also reduced the level of plasma TNF-α. T, thus reduce the intestinal inflammation (Stul *et al.*, 2018).

However, these days, scientific findings had revealed that edible insect offers more than proteins and nutrients for human consumption. The current trend is now focusing to reveal the potential of edible insect for nutraceutical and pharmaceutical industry. However, this scope of study is newly explored and the information regarding the bioactive compounds in edible insects are remains severely limited. Our comprehensive exploration on published literature review shows that several studies demonstrated the possibilities of edible insect to act as anti-inflammatory, antioxidant, antiangiogenic, antihypertensive, antidiabetic, or antilipidemic (Table 2); thanks to the bioactive compounds found in those insect body. The composition of these bioactive compound is due to the insect absorption and metabolization of the plant-derived phenolic present in the herbivory insect diet (Nino *et al.*, 2021). In addition to that, insects also have the ability to synthesize phenolic compounds de novo through the sclerotization process (Nino *et al.*, 2021).

Lepidopterans seem to contain large amounts of phenolic compounds obtained from their host plants that able to have a key role in specific bioactivities (Table 3). Fu *et al.* (2021) reported that over 200 flavonoid metabolites were detected in the larval midgut of *A. pernyi*, a large saturniid species. These flavonoid metabolites comprised of flavones, flavanols, flavonoids, flavanones, polyphenols, isoflavones, anthocyanins, and proanthocyanidins. In another research by Sheileja *et al.* (2022), the bamboo worm *Omphisa fuscidentalis* had sufficient amount of phenol (53 mg/100 g) and tannin (62 mg/100 g) that important for antioxidant activities. In addition to that, the edible Congolese caterpillars of the genus *Cinabra*, *Gonimbrasia*, and *Imbrasia* were found to contain phenolic acids, flavonoids, and terpenes (Kapepula *et al.*, 2022). The uptake of food that rich with phenolic acid may reduce the risk of many oxidative stress related diseases viz. cancers, diabetes and cardiovascular (Kumar and Goel, 2019). Flavonoids not only well known with its antioxidant properties, but also have neuroprotective and cardio-protective effects (Ullah *et al.*, 2020). Meanwhile, terpenes have anti-inflammatory effects and has potential to cure disease such as bronchitis, chronic obstructive pulmonary disease, skin inflammation, and osteoarthritis (Cho *et al.*, 2017).

Mlcek *et al.* (2014b) reported that some species of Lepidoptera has antimicrobial and antifungal peptides. These peptides are pivotal elements for human body against bacterial and fungal infections. As an example, *B. mori* had lebocin, orcecropin, attacin, lysozyme, and moricin. *Galleria mellonella* had eight antimicrobial peptides. Insect metalloproteinase inhibitor and antimicrobial peptides from *G. mellonella* may provide promising templates for the rational design of new drugs since evidence is available that the combination of antibiotics with inhibitors of pathogen-associated proteolytic enzymes yields synergistic therapeutic effects (Vilcinskas, 2011).

TABLE 3 Phenolic compounds of edible Lepidoptera species

Species	Phenolic compounds	Reference
Antheraea pernyi	Hyperoside (quercetin 3-O-glucoside), isoquercitroside, tricin 7-O-hexoside, hesperetin 5-O-glucoside, protocatechuic acid, luteolin 7-O-glucoside (cynaroside), kaempferol 3-O-glucoside (astragalin), C-hexosyl-luteolin O-p-coumaroylhexoside, luteolin 6-C-glucoside, tricin 40-O-(β-guaiacylglyceryl) ether O-hexoside, orientin, luteolin C-hexoside, kaempferol 3-O-galactoside (trifolin), and tricin 4 0-O-(β-guaiacylglyceryl) ether 7-O-hexoside	Fu *et al.* (2021)
Bombyx mori	Quercetin, kaempferol, quercetin 5-O-β-D-glucoside, quercetin 7-O-β-D-glucoside, quercetin 4'-O-β-D-glucoside, kaempferol 5-O-β-D-glucoside, kaempferol 7-O-β-D-glucoside, quercetin 5-glucoside, quercetin 5,4′-diglucoside, quercetin 5,7,4′-triglucoside	Nino *et al.* (2021)
Coenonympha pamphilus	Tricin (40,5,7-trihydroxy-30,50-dimethoxyflavone)	Aiello *et al.* (2023)
Lysandra coridon	Kaempferol, kaempferol 7-rhamnoside, kaempferol 3-rhamnoside, kaempferol 3-glucoside, kaempferol 3-glucoside, 7-rhamnoside, quercetin 3-glucoside, quercetin 3,7-diglucoside, isorhamnetin 3-glucoside, isorhamnetin 3,7-diglucoside	
Melanargia galathea	Tricin (40,5,7-trihydroxy-30,50-dimethoxyflavone), apigenin (4,5,7-trihydroxyflavone), tricin 7-glucoside, orientin (8-glucosylluteolin), luteolin 7-diglucoside, orientin 7-glucoside, vitexin 7-glucoside, isoorientin (luteolin 6-C-glucoside), isovitexin (6-C-glucosylapigenin), and tricin 40-conjugate	Aiello *et al.* (2023)
Pieris brassicae	Kaempferol glycosides and ferulic and sinapic acids	Aiello *et al.* (2023)
Polyommatus icarus	Quercetin, kaempferol, and quercetin-glycosides and kaempferol-glycosides	Aiello *et al.* (2023)
Polyommatus bellargus	Kaempferol and quercetin glycosides	Nino *et al.* (2021)
Rondotia menciana	Quercetin-glycosides and kaempferol-glycosides	Hirayama *et al.* (2013)

6 Harvesting and rearing of edible Lepidoptera species

Traditional ways of edible insect collecting and harvesting in the wild

There are three ways for obtaining edible insects including wild harvesting, semi-domestication, and farming. About 92% of documented edible insect species are obtained by wild harvesting, 6% species are obtained through semi-domestication, and merely 2% are obtained through farming (Yen, 2015b). Therefore, the development of insect production departments proposed a strategic solution for solving the issues of food insecurity (Ayieko *et al.*, 2016; Kelemu *et al.*, 2015). Mini livestock recognizes those edible insects and some other small-sized animals, which can be husbanded, and usefully disbursed by humans (Abbasi *et al.*, 2016). There are many environmental pressures to all edible insects, including deforestation, insecticides, fragmentation of habitat, and climate change (Dover *et al.*, 2015). Therefore, the establishment of rearing methods would provide a constant source of edible insects, with less effect on the environment. Additionally, the monitored production of edible insects would assist to decrease health hazards related with ingestion of insects, by evading the probable bioaccumulation of harmful substances which can be dangerous for consumers health includes pesticides, toxic plants, and polluted farmed areas (van der Spiegel *et al.*, 2013). Wild edible insects are probably barer to microbiological impurities, while raising insects in farms permits the farmer to identify, control, and assure the production environments and consequently, decrease the risk of microbial contagion (Caparros Megido *et al.*, 2017).

Conversely, if there is absence of hygiene practices and disinfection methods during breeding, edible insects can be polluted with pathogens at any phase of the processing and handling, including production,

TABLE 4 Benefits of rearing edible insects

General management benefits	Health benefits	Environmental benefits	Economic and Social factors
Products consumption is not directly but can be used in livestock feed	Insects provide good substitute of animal proteins as compare to pork, chicken, beef, and even fish	Precise emission of greenhouse gases and ammonia by insects are far less as compare to other livestock	Harvesting and rearing of insects have simple technique and capital investment choices can be possible even in the poorest societies
Demand is more than supply	Insect species have high quantity of proteins, body fats and enough calcium, zinc and iron	Insects nurturing needs very less land and water as compare to other livestock	Nourishment of insects offers opportunities for maintenance of both urban and rural inhabitants
Insects have short life cycles and can be easily transported	Insects are already used as diet for several nations	Insects are cold-blooded animals; their efficiency in converting food into protein is very high.	Harvesting of pest insect species as food would be a perfect alternate to increase food production and dropping pest pressure on cultured crops
Insects are more nutritive for humans with higher feed conversion ratio	Risk of transferring zoonotic infections to livestock and humans might be less through insects as compared to mammals and birds	Edible insects can grow on organic side-streams (manure, compost and human waste) with sustainability, so can be helpful in decreasing environmental pollution	Fast earnings on investment and high financial revenues
Insect's husbandry does not need profound training	Insects can be used in medicines because of containing antioxidants		

assembly, desiccating, storing, transportation, and delivery (Palomino-Camargo *et al.*, 2018). Avoiding these possible risks linked with consumption of edible insects, it is perfect to eat those insects which have been grow on farms in controlled environment by following completely hygiene and sterilization protocols throughout the processing and delivery stages (Payne *et al.*, 2016). Therefore, now Directorate General for Agriculture and Rural Development of the European Commission is working on provision of the authorization on insect's production accomplishments for human consumption (Pino Cebrián, 2018). Compared to other food sources, the advantage of insect farming, are given in the following Table 4 (Wilson, 2012; Mlcek *et al.*, 2014a).

The physical gathering of insects, particularly that are pests, can protect crops and beneficial for the ecosystem by decreasing the application of pesticides (van Huis *et al.*, 2013). In underdeveloped countries, edible insects are usually harvested in the wild by applying different harvesting methods on the basis of insect's behavior, also collecting region. These methods vary from handpicking to applying particular tools including glue, nets, sticks, and baskets (Niassy *et al.*, 2016). For instance, termites and grasshoppers are collected by using light traps and dragonflies are collected by using sticky liquid from fruit trees (Raheem *et al.*, 2019a). While edible caterpillars like *C. forda* and *I. oyemensis* are normally collected by hand picking (Gahukar, 2020).

Harvesting from wild is the most prehistoric and utmost labor-intensive method that established over many experiences and attentiveness of the daily and seasonal availability of insects for collection. For instance, the stink bugs in south Africa are collected early morning in less hot time period when insects are sedentary; by shaken down them from tree branches with a long bamboo stick and a bag attached at the end. Many other tools are also developed for efficient harvesting. For instance, collection of insects through sound or light are also reported (van Huis, 2018). In the Democratic republic of Congo, the caterpillars of *C. forda* and *G. belina* are harvested in the wild are located into trees nearby huts and collected when a family wants or needs this type of diet (Latham, 2015). Some species of caterpillars are remained to pupate in common natural places to increase the population of insect as a form of ethical foraging or wild harvesting (Latham, 2015). Usually, fully developed larvae of Lepidoptera and nymphs of grasshoppers, termites, and some other insects are gathered and preserved on plastic trays, in bags or cups to be ready for selling. In the marketing courtyard, insects selling are charged with administration taxes which eventually decrease the cost-effectiveness for sellers (Mmari *et al*., 2017). Mostly, edible insects were harvested for human feeding, but sometime they can also use for animal feed (Van Huis, 2022; Nura *et al*., 2021). Silkworm pupae are an important insect food in the record of new food sources established by the China Ministry of Health, and are broadly used in nutritional supplements, pharmaceuticals, and animal feed in Korea and China (Govorushko, 2019). For instance, Silkworm pupae are used as fishmeal for propagation of fish, crustacean and poultry because of having digestibility and antioxidant ability (Rahimnejad *et al*., 2019; Sun *et al*., 2014). Besides human consumption of silkworm directly or in the form of food ingredients, the human requirement for food protein can be accomplish by adding silkworm pupae in animal feedstuff (Han *et al*., 2017).

Edible caterpillars are collected in savannahs, forests, and in further unrefined territories depend on the time and place of harvesting recognized by farmers (Yen, 2015b). Generally, edible caterpillars are collected physically by children and women on the land, trunks, leaves, and branches of plants where they are placed (Muya *et al*., 2022). Some farmers hit the trunks of large trees with hammers to access the caterpillars or used a lengthy bamboo stick to hit the tree for falling of caterpillars, though some cultural groups from Central African Republic hike trees to collect those (Muya *et al*., 2022). Edible caterpillars are also collected by cutting host plants. For instance, in the Democratic republic of Congo, 65% of respondents identified that they cut the trees for collection of utmost usually consumed species of caterpillar involving *C. forda* and *Imbrasia* spp., although it's not a suitable practice for maintenance of ecosystem (Vantomme, 2015).

Previously, harvesting of caterpillars was controlled by following parameters, including observing abundance of host plant and potential modifications to the environment; protecting susceptible phases of life and particular territories; and identifying exact timing of collection (van Huis and Oonincx, 2017). Assessment of each species should involve the identification of biological features, like host plant, distribution, species specificity, variety of host plants, ability of dispersion, and many other parameters of life history. The seasonal accessibility of edible caterpillars fluctuates with different area and climatic situations (Kusia *et al*., 2021). This availability of caterpillars is associated with the occurrence of host plants on which caterpillar feed at starting time of the raining season, since caterpillars definitely feed on one or more than one host plants that solitary grow in specified ecosystems (Mabossy-Mobouna *et al*., 2016). For instance, *C. forda* caterpillar feed on different host plants in different regions like on *Autranella congoensis* in Central African Republic, on *Vitellaria paradoxa* in West Africa, on *Crossopteryx febrifuga* in Bas-Congo province of Democratic Republic of Congo, on *Burkea africana* in South Africa, on *Albizia antunesiana* in Katanga, and on *Erythrophleum africanum* in Bandundu (Latham, 2015). Another important type of caterpillar, *G. belina*, is important in Southern Africa. Occurrences of *G. belina* take place mostly on miombo (*Brachystegia* sp.) and mopane (*Colophospermum mopane*) trees in forests from the Atlantic to the Indian Ocean. The larvae of *G. belina* are good source of food during long distance travelling and economically important among countryside populations (Makhado *et al*., 2014).

There are many problems associated with harvesting process including improper timing and duration of the collecting period, damaging methods of collection, collecting high amount of insects and below age insects, fire wood collection, and trampling. Overharvesting is also an issue happened in scarcity of food or sometime due to high income profit from the trading of edible insects. In common regions, principles might include harvesting licenses that control the figure of collectors, place of collection, amount and mass of caterpillars which is collected, establish non-harvest zones like wildlife assets, and numeral of days in which a harvester can do harvesting (Kuniyal and Sundriyal, 2013; Mufandaedza *et al*., 2013; Thomas, 2013).

Security of safety and quality from wild collection of insects cannot be assured. Semi-domestication is a good alternative solution of conserving edible insects.

Semi-natural rearing system

Insects can be raised and farmed for both human and animal food by using two methods: first is insects can be completely domesticated and raised in confinement, and the second is incompletely raised in confinement, changing the insect habitation to upsurge production but, usually, devoid of isolating them from their wild communities. So, different methods of farming can be applied (Feng *et al.*, 2018). Cockroaches and mealworms are perfect contestants to farming both at domestic and industrial level because of their nurturing situations has been widely studied. Some insects can be raised in plastic greenhouses and some insects can be nurtured in semi-natural environment by giving proper care to their feeding (Feng *et al.*, 2018). Some insects including locusts, bamboo caterpillars, wasps, dragon flies, and palm weevil larvae fit in the second type known as semi-domestication. Amendments in natural environment to obtain edible insects are known as semi-domestication.

Semi-domestication includes the transmission of insect varieties to some other breeding places or the modification of territories (Ngute *et al.*, 2020). Very less examples of semi-domestication of edible caterpillars are existing. Some edible caterpillars including such as *Lobobunaea phaedusa* and *Imbrasia* spp. are transported from wild forests trees to domestic trees nearby to the lodgings of villagers (Niassy *et al.*, 2016). This activity permits larvae to carry on their growth in a location where they are retained benign from heat, drought, and predation, which can be causes of their transience in the natural environment (Niassy *et al.*, 2016; van Huis *et al.*, 2013). In Bas-Congo, province of Democratic republic of Congo, the edible caterpillars are presented to villager communities by putting them on trees nearby to the farmers houses (Latham, 2015). One farmer used this assistance scheme by placing *C. forda* caterpillars to a grassland territory plentiful with host treed, and afterwards recurrently collected caterpillars from this territory (van Itterbeeck and van Huis, 2012). The happenings adjoining semi-domestication include both protection of edible insect territory and security of food (van Huis *et al.*, 2013). For instance, bamboo caterpillar's *O. Fuscidentalis* were raised on bamboo shoots shielded with nylon net birdcages (Durst and Hanboonsong, 2015).

Some laboratories are presently trying to rear insect's *in-situ* to meet the requirements of few people who rear them *ex-situ* for demanding and extensive scale production in the upcoming future (Monzenga, 2015; van Huis, 2022). The rearing process of edible caterpillars (Lepidoptera) faces numerous difficulties. First of all, it is essential to have a locality where the food plants or other plants are well developed as well as short length plants are ideal. If trees are available on site, their length should be cut to about two meters. Secondly, to stop numerous unwanted insects or predatory insects from existence or entering in the rearing capacity, a very small net must be used and make sure that net has not stolen by local people. One more compulsory step is to bring male and female insects of the lepidopteron species together to be bred. For this purpose, put chrysalises in crates placed them in the locality and visited on a regular basis will allow the quick introduction of grownup insects into the rearing capacity (Konda and Ambühl, 2019).

Entomopathogens are known as pathogens which cause insects infections and diseases. These entomopathogens can be bacteria, virus, fungi and nematodes. The accidental introduction of entomopathogens in the rearing capacity can cause high rate of mortality in reared insects due to epizootic. Most bacteria like *Bacillus thuringiensis* (Bt) can kill beetles and caterpillars by producing insecticidal toxins known as "Cry proteins" which caused damage of insects gut epithelium (Marchetti *et al.*, 2012). Generally, viruses cause 70% to 80% loss in cocoon yield by producing disease in silkworms. Major kinds of viral diseases in the silkworm were identified as nucleopolyhedrovirus, cytoplasmic polyhedrosis, and densonucleosis. Rate of bacterial infections is lower in silkworms, only happened because of insufficient rearing requirements and lack of hygiene. Bacterial disease known as flacherie occurs by *Enterococci* causing diarrhoea, and leads to death of the contaminated insects (Eilenberg *et al.*, 2015). Entomopathogenic fungi also cause damage of Lepidoptera insects, like Hypocreales fungi can infect a broad range of insects. Fungi have been reported to infect many types of insect including lepidopterous larvae, aphids, mites and thrips (Sharma and Sharma, 2021).

Rearing of insect involves giving it the excellent potential diet at each life stage, either larva or adult, and correspondingly generating the preeminent environment for insects to rise. Moreover, observing their behavior for long time in terms to give them suitable environment according to their behavior (Halloran and Vantomme, 2019). The crucial points to efficacious rearing are significance of insect species that are rearing, which regularly includes considering the outcome of insect feeding practices, considering microbial interactions in the diet, discovering food constituents and subsequent quality of insect, evaluating food chemistry, and environmental development controls (Cohen, 2015). Insect diet mentions to the food commonly consumed by insect for growth, reproduction, tissue maintenance, and to get energy (Chapman, 2012). Most insects con-

TABLE 5 Nutrients required for the growth of insects in semi-domestication (Data source: Cohen, 2015)

Nutrients	Sub nutrients	Function
Macronutrients	Carbohydrates: monosaccharides, disaccharides (glucose, fructose, sucrose, and maltose), starch, and other polysaccharides (cellulose)	Used as respiratory fuel, offers carbon basis for formation of organic molecules, and organize building constituents from polysaccharide for the insect cuticle
	Lipids: polyunsaturated fatty acids, phospholipids, and sterols	Vital source of energy and used as essential constituent of cell membrane, serve as nutrient carriers, as pheromones and as defensive complexes. Sterols are used in the formation of ecdysteroid/molting hormones and fatty acids used for the formation of adolescent hormone
	Proteins: polypeptides, glycoprotein, and lipoprotein	Required for many biological functions, like formation of cell structure and enzymes, storage and transport, receptor molecules
Micronutrients	Minerals: calcium, chloride, copper, iron, magnesium, manganese, phosphorus, potassium, and sodium	Synthesis of coenzymes and metalloenzymes, excitability of tissues performers of the bioenergetics activity like glycolysis pathway
	Vitamins: β-carotene, tocopherols, choline, and carnitine	visual pigments development and function, helps in fertility factor including spermatogenesis and egg maturation, formation of cell membrane, lipid metabolism

sume similar quality of nutrients including macronutrients and micronutrients (Cohen, 2015; Siddiqui *et al.*, 2022), which have given in the Table 5 with their functions.

There are many other important aspects which make rearing process of insects difficult. For maintaining the insects rearing facility these aspects should be maintained including insect background, proper food, environmental conditions (temperature and humidity, gas exchange, energy and metabolism, and light conditions), microbial contamination and genetics (Cohen, 2018).

To prevent insect diseases and to regulate the production of insects in specific location, some parameters should be controlled in rearing capacity of insects (Morales Ramos *et al.*, 2014). When insects are taken to the rearing capacity, only few of them can survive and reproduce therefore genetic variety in a reared population of insect will become considerably less as compared to natural population. After bringing insects into rearing capacity quick diagnosis, should be performed to check any unknown reason of insect's death which can be occurred due to any infected host. After this, all contaminated or odd insects ought to be removed instantly and ruined them for optimum clean rearing environment. For removal of microorganisms disinfectants should be used but in more serious situation, insect cages should be sterilizes by using UV light (Lacey, 2012).

Genetic variability in insect's populations should be maintained then diseases can be managed successfully. Introduce newly captured insects into already existed insect's colony after regular time period to obtain new traits into previous population by mating with them to broaden the genetic variety of reared population and to generate stronger and extra productive insect entity as compared to previous generation (Hoffmann *et al.*, 2021; Nakajima and Ogura, 2022).

Harvesting insects from natural habitats is usually difficult since maximum forest insects are available only through the rainy period or when entree to natural insect habitats is prohibited by forest authority consultants. In these circumstances insects can be raised in laboratory, for instance, tasar silkworm *Antheraea mylitta*can grow on host plants in wide-mouth bottles, in mud pots, or in conical flasks, by feeding on artificial diets. This method is more suitable and has less chances of contamination. Adding of host plants (*Terminalia elliptica* and *Terminalia arjuna*) leaf powder to the laboratory feed supply led to in considerably better survival of fresh larvae and quicker growth of later stages of tasar silkworm as compared to nourishing on fresh leaves (Kumar *et al.*, 2013).

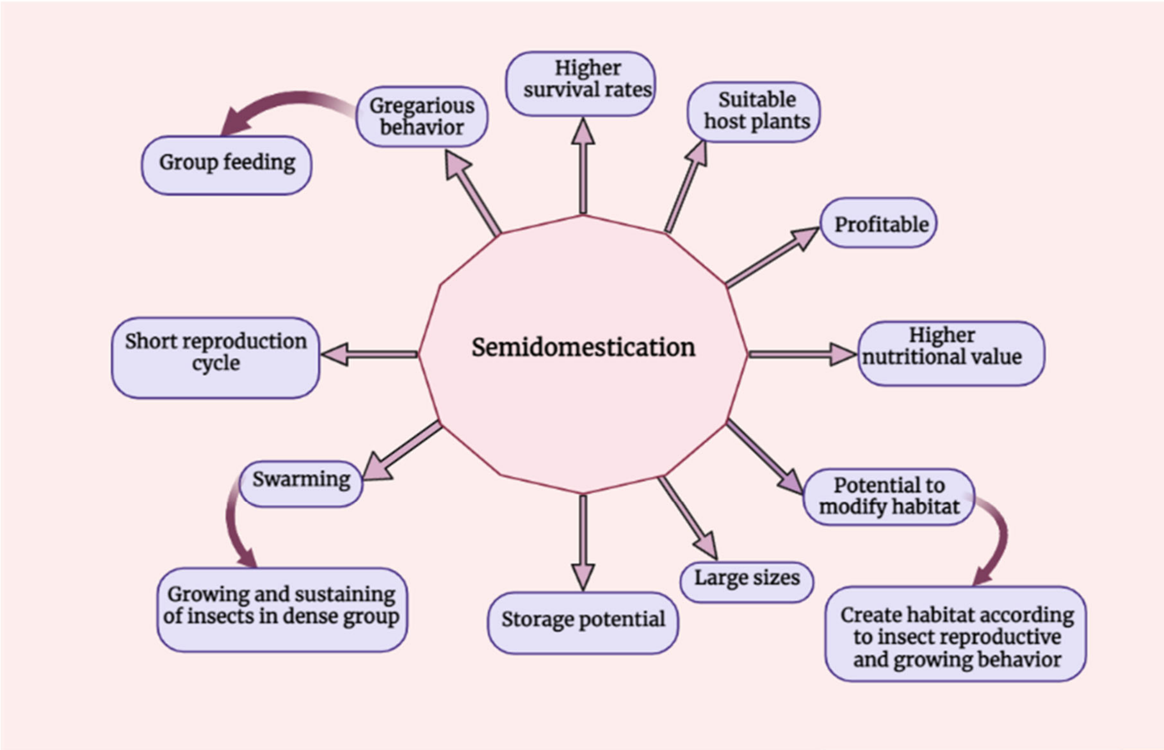

FIGURE 6 Parameters of insects and habitat selection criteria for semi-domestication.

It was documented that there are some necessary parameters for semi-domestication in terms of insect's properties and appropriate environment for their raising. Those characteristics include a short reproduction period of insects, insects production should be in bulks, gregarious behavior like feeding on host plant in groups, swarming, high rate of insect's reproduction, greater survival abilities of insects, higher nutritive value of insects, storage potential, there should be potential to modify or create habitat according to insect reproductive and growing behavior, suitable host plants, with ability to host more than one type of edible insects concurrently and should be easily cultivated, and raised insect species should be commercially important (Figure 6) (van Huis *et al.*, 2013).

7 Legislation on Lepidoptera as food and feed: worldwide comparison

Insects are consumed by many ethnic's groups especially in Asia, Africa, North and South America with the majority of edible insects are belong to order Lepidoptera, Orthoptera, Coleoptera, and Hymenoptera (FAO, 2021). Entomophagy is a new phenomenon for western countries, while in some poor countries such as in Africa, entomophagy was commonly practice reducing malnutrition by providing a sustainable, cheap, clean but nutritional source of protein. Meanwhile in some countries in Southeast Asia such as Malaysia and Thailand, entomophagy is more classified as enjoying comfort food practices that provides a nostalgic or sentimental value to the people who consumed. Nowadays, entomophagy also become part of human recreation activity where it may generate income to many less developed countries (Yen *et al.*, 2013).

Since entomophagy are related to insect farming or collecting insect in the wild activities, it was regulated mainly in three different contexts which are food law, wildlife resources management, and pest management (Grabowski *et al.*, 2020). Several countries had issued national guidelines as recommendations and interim solutions in preparing food legislation. However, the regulation of insect as food and feed are fragmented and are differs among countries worldwide. These has been discussed comprehensively by Lähteenmäki-Uutela *et al.* (2021). In addition to that, only few insect species have been submitted to be reviewed under those legislation.

Although African countries has a high diversity of insect species and demand for insect protein, there is no specific legislation on insect production or insect foods (Niassy *et al.*, 2018). Similar to that, there is no legislation on entomophagy at the Asian countries as people have felt comfortable with insects' presence in the food chain (Raheem *et al.*, 2019b). Meanwhile, there are only seven species of insects were submitted to be declared as novel food products in European Union. Those insects are house cricket (*Acheta domesticus*), banded/tropical house cricket (*Gryllodes sigillatus*), lesser mealworm (*Alphitobius diaperinus*), black soldier fly (*Hermetia illucens*), honeybee (*Apis mellifera*), migratory locust/grasshopper (*Locusta migratoria*), and yellow mealworm (*Tenebrio molitor*) (Lähteenmäki-Uutela *et al.*, 2021) with no lepidopteran insect was included in that list. According to Commission Regulation (EU) 2017/893 of 24 May 2017 [14] amending Annexes I and IV to Regulation (EC) No. 999/2001 [42] of the European Parliament and of the Council and Annexes X, XIV and XV to Commission Regulation (EU) No. 142/2011, these insects' species had fulfilled the safety requirements for insect production for feed use. However, insect had a limited use as food in European countries. Thus, the International Platform of Insects for Food and Feed (IPIFF) was established to promotes the use of insects for human consumption and insect-derived products as source of protein for animal feed. In the United States of America, the legislation regarding insect as food is put under the stewardship of the US Food and Drug Administration (FDA); where insects are considered as food under the Food, Drug, and Cosmetic Act (United States Code, Title 21).

Even though insects were regarded as a safe source of alternative protein, legislation was made as the consumption of edible insects was believed may lead to consumer risks, typically allergens, foodborne diseases, food spoilage agents, and contaminants due to their microbiological safety for consumers has not yet been fully clarified (Gałęcki *et al.*, 2023). As an example, Badanaro *et al.* (2021) reported that caterpillar of *C. forda* was contaminated with bacteria such as *Staphylococcus* spp., *Escherichia coli*, *Enterobacter* spp., *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Proteus* spp., *Serratia* spp., and fungi such as *Aspergillus niger*, *Aspergillus flavus*, and *Mucor* spp. These microorganisms are pathogenic and detrimental to the human health and may exposes consumers to the risk of food poisoning due to the toxins they produced.

In order to fulfil the demand, insects were farmed. As an example, *G. belina* was farmed intensively in Sothern Africa with the yearly trade value of more than US $85 million (Bara *et al.*, 2022). However, there were some species of edible lepidoptera that identified as crop pest; thus, farming those insects' species may become a threat for agriculture industry if it does not farm properly. Grabowski *et al.* (2020) has listed several species of edible lepidopterans that were put under specific acts in African countries as these species are plant pests (Table 6). These acts responsible to protect agriculture industries in African countries. Our comprehensive literature reviews did not find any other specific legislation were made on the edible lepidopterans. Most of the reports and comparative review on the global regulations on insects as food and feed only explained the legislation of general insects with no separate discussion on specific insect such as Lepidopera (Grabowski *et al.*, 2020; Lähteenmäki-Uutela *et al.*, 2021).

8 Consumer acceptance of edible lepidopterans as food

Consumption of insects has existed for over thousand years, in some cases as emergency food, or as a staple, and in other instances as delicacies (Durst *et al.*, 2010). In recent times, however, there is a consistent push for insect consumption. FAO at their meeting in 2012 came up with a strategy to promote global insect consumption, mainly due to their many positives such as their high nutrition, potential to contribute to sustainable life on Earth, and as functional food. Insects are eaten either fried, roasted, boiled, and even sometimes raw. In some instances, insects are consumed with or without the knowledge of the consumer, such as in the cases of rice weevil *Sitophylus oryzae*, maize weevil *Sitophilus zeamais*, and the larger grain borer *Prostephanus truncatus* as well as many other grains and cereal storage pests. According to FAO (2013), insects can be presented in different forms; as whole insect, in powder or paste, and as protein extract. Entomophagy generally seems to be a cultural phenomenon. It has been proven scientifically that consumer acceptance of a certain food can be controlled by cultural, personal, and emotional factors (Verbeke, 2015). From the list of edible lepidopterans presented here, it is observed that in most instances the species are continent specific. With the above observation it could also be argued that consumer acceptance of certain species is based on availability or native of distribution.

Most works done on consumer acceptance of insects as food were from the Western world such as Europe and the North America (Clarkson *et al.*, 2018; Deroy *et al.*, 2015; House, 2016; Looy *et al.*, 2014; Tan *et al.*, 2016; van Thielen, 2018). Little work is done in Africa or Asia to ascertain consumer acceptance. This could be attributed to the fact that in these continents, insect consumption is natural and actually a delicacy in most cases. Hence, the perceived perception that ento-

TABLE 6 Edible Lepidoptera legislation in African countries (Grabowski *et al.*, 2020)

Species	Country	Law
Cossus cossus	Algeria	Décret exécutif nº 95-387
Chilo spp.	Kenya	Plant Protection Order
	Mozambique	Decreto nº 5/2009
Ostrinia furnacalis	Botswana	Plant Protection Act 2007
Pectinophora gossypiella	Zambia	Plant Pests and Diseases (Pest Control) Regulations, Plant Pests and Diseases (Pests and Alternate Hosts) Order
Busseola fusca	Kenya	Plant Protection Order
Helicoverpa spp.	Cape Verde	Portaria nº 37/2015
Heliothis spp.	Botswana	Plant Protection Act 2007
	Seychelles	Plant Protection Act
Heliothis zea	Tunisia	Arrêté du Ministre de l'agriculture du 31 mai 2012
Spodoptera spp.	Botswana	Plant Protection Act 2007
	Mozambique	Decreto nº 5/2009
	Tunisia	Arrêté du Ministre de l'agriculture du 31 mai 2012
Spodoptera frugiperda	Mozambique	Decreto nº 5/2009
	South Africa	Control Measures Relating to Fall Armyworm
	Tunisia	Arrêté du Ministre de l'agriculture du 31 mai 2012
Pieris spp.	Mozambique	Decreto nº 5/2009
Chilo spp.	Benin	Arrêté interministériel nº 128
	Botswana	Plant Protection Act 2007
Acherontia styx	Mozambique	Decreto nº 5/2009
Agrius convolvuli	Botswana	Plant Protection Act 2007
Clanis bilineata	Mozambique	Decreto nº 5/2009
Erinnyis ello	Mozambique	Decreto nº 5/2009

mophagy is a common practice mainly in areas where food security is very low and people cannot afford to choose their source of nutrients (Nadeau *et al.*, 2015) and 'food for the poor' is disputable (Bednarova, 2014). This is reiterated by Bartkowicz and Babicz-Zielinska (2020), consumption of insects is not due to lack of other food but because of the special taste. In urban areas, consumers of various economic standings are willing to pay for insects from vendors either processed or whole insects from supermarkets or local markets (Alemu, 2015; Bae and Choi, 2021). In the Western world, however, insects are mainly classified as pests and the idea of entomophagy is usually associated with disgust, primitive, and in some cases, insects are considered as unhygienic and habouring diseases (Bartkowicz and Babicz-Zielinska, 2020; Bednarova, 2014; Belluco *et al.*, 2013). Entomophagy is gradually being introduced to the West with the backing of organisations such as the FAO. Works done on consumer acceptance of insects among the Western societies have yielded mixed results. Fewer consumers are willing to try whole visible insects, others are willing to try processed insects, such as insect powders or protein extracts incorporated into other food products such as pizzas, snacks, drinks, and bread, and other group of people are just not willing to try it (Bae and Choi, 2021; Bartkowicz and Babicz-Zielinska 2020; Clarkson *et al.*, 2018; Karnjanapratum *et al.*, 2022; Megan and Beacom, 2021; Naranjo-Guevara *et al.*, 2020; Tan *et al.*, 2016; van Thielen *et al.*, 2018).

Countries with large agricultural sector and high meat consumption are more reluctant in trying alternative meat substitutes, not to talk of insects (Clarkson *et al.*, 2018). In New Zealand for example, where meat production is high, they seem to be reluctant in trying insects as alternative protein source. As is recorded by a respondent in insect consumer acceptance survey "if we want protein we'd go for a hunk of meat, not a little crawly thing" (Clarkson *et al.*, 2018). Meat lovers would in no way substitute insects as meat, but rather would try other meat substitutes that mimic meat in taste and familiarity (Tucker, 2014). Many authors have also recognized that the negative response to entomophagy in the West can be attributed to lack of education (Clarkson *et al.*, 2018; Schösler *et al.*, 2012; Verneau *et al.*, 2016).

Over the years, records show that there is decline in entomophagy in developing countries and suggestions imply that this could be due to the infiltration of western coulter into developing countries (Nadeau *et al.*, 2015). More work is needed, however, to verify this claim. In recent times, however, and with some more emphasis, education and actually presenting the insects, some Westerners are more willing to try eating insects (Bartkowicz and Babicz-Zielinska, 2020; Clarkson *et al.*, 2018; Megan and Beacom, 2021; Naranjo-Guevara *et al.*, 2020). Different awareness creation avenues are making eating insects more familiar, hence shaping people's perception and attitude (Verbeke, 2015). There are more studies on the subject, more publications, and even more advertisement on edible insects. It has been reported that in Germany for example, various advertising strategies such as popular media, newspaper articles and TV documentaries have had positive impact on consumers (Berger *et al.*, 2018). It is also reported that in the last decade, many insect companies are opening up in different European countries such as France, UK, Belgium, the Netherlands, and Germany (la Barbera *et al.*, 2018; Orsi *et al.*, 2019).

There is a study carried out by van Thielen *et al.* (2018) on consumer acceptance of edible insects in Belgium. In this study they considered different categories of respondents including age and gender. His questionnaire was based on; (1) respondents who already ate insect-based foods; (2) respondents who did not yet eat insect-based foods but with interest to do so; and (3) respondents who did not eat insect-based foods and with no interest to do so. In their findings based on gender, one interesting observation made was that young men are more willing to try edible insects than women (67.4% to 32.6%). These are people who have had experience in entomophagy and still have the interest, and for the group of people who have had no experience and no interest, women were in the majority with a percent of 58.1% women to 41.9% men. This confirms the observation of Verbeke (2015) and Hartmann *et al.* (2015) who said young men are more likely to accept insects as food. However, it was also observed that the influence of age on entomophagy is not certain, as it is also observed by Verbeke (2015) that willingness to eat insects correlates with age, but it is not the case by Hartmann *et al.* (2015). Tao and Li (2018) also observed a strong correlation between age and willingness to try eating insects, where about 76 % are between 18-24 years old as against 1% who are over 55-years old (Figure 7).

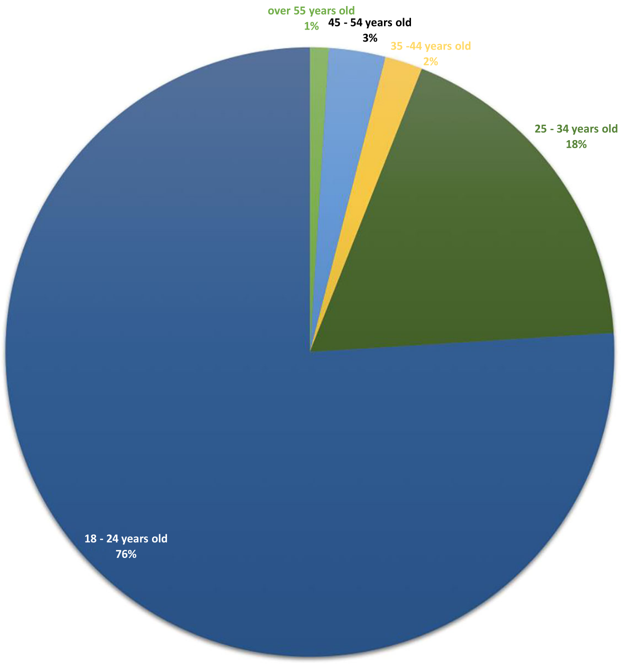

FIGURE 7 Entomophagy with relation to age (derived from Tao and Li, 2018).

In the study by Clarkson *et al.* (2018), participants were made to design their own insect-based food products, and about 52% of the products designed were targeting children. The idea was that 'kids are adventurous to try insects'. Participants also believed that children, being the future generation, will grow up eating insects, adding that 'they will grow up to normalize it from a young age'. Indeed, for entomophagy to be well established in the West, children are the most suitable. Adults have already established their disgust perception around the subject, and it will take a whole lot than encouragement and education to change their mind. A cultural reorientation is needed to be able to push the edible insect agender, and this starts with children.

Religion also plays a role in the acceptance of insects as food. In Islam for example, there seem to be varying schools of thought on the subject. Whiles locust consumption is halal (widely accepted) due to its consumption by the spiritual leaders in the Quran, there is division when it comes to other insects. Some regard them as haram (completely unacceptable), others as halal, others still as filthy, therefore not halal but not necessarily haram (Rahim, 2018; Tajudeen, 2020). However, as elaborated by Tajudeen (2020) all schools of thought agree that insects growing out of food, such as food worms, are halal and permissible. With this said, among others, such as it being 'good and acceptable, hygienically and spiritually wholesome' the decision to accept insects as food is left to the individual to decide based on the school of thought one belongs to.

Insects as animal feed seem to be more acceptable to consumers than as human food. This is clear from the study conducted by Naranjo-Guevara *et al.* (2020)

where about 84% of the respondents were willing to accept insects as animal feed with this number reducing to 48% of those willing to accept insect as human food.

As concluded by many authors, acceptance of insect as food, and hence edible lepidopterans, depends on the form of presentation. Especially for developed countries where entomophagy is very limited, the few who say they may consider eating insects say they would prefer 'invisible' insects that is as powder or protein extract to whole insects (Alemu *et al.*, 2015; Clarkson *et al.*, 2018; van Thielen *et al.*, 2018). Durst *et al.* (2010) noted on that despite the benefits, entomophagy is not likely to become accepted as a mainstream dining option in Europe and North America anytime soon. Developing insect protein extracts, processed foods and animal, however, can maximize the potential of edible insects worldwide. Many potential consumers say that incorporating edible insects into familiar preparations such as pancakes, smoothies, and snacks can actually influence their acceptance (Naranjo-Guevara *et al.*, 2020).

Health consciousness as well as good packaging are very important in the choice or acceptance of food by consumers (FAO, 2013). In view of that, FAO (2013) encourages that administrative frameworks should be developed such as standardization to control food safety and legalization. This can also go a long way to allays people's fear and health concerns and encourage entomophagy. Pupae of silkworm *B. mori* is one of the widely accepted and consumed lepidoptera Asia. They are canned and exported to many international countries (Kang *et al.*, 2012).

9 Future perspectives and conclusion

Global population is increasing which can leads to the deficiency of food sources. In the meantime, edible insects are good alternative source to fulfil the requirement of food. Edible insects have high nutritious value and are good source of protein and many other macronutrients and micronutrients as compared to other livestock animals. Additionally edible insects can be used as food additives, nutraceutical and also in pharmaceutical due to the presence of antioxidants. In this review our main focus was on Lepidoptera which is an important insect order with above than 188,359 species which belongs to 4,000 genera. At present anthropo-entomophagy considered more than 2,100 insect species, from which edible Lepidoptera have around 350 species or more. Edible Lepidoptera can be consumed during pre-adult stages (caterpillars and pupae) or adult stage (moths and butterflies).

Farming and harvesting of Lepidoptera insects for food purpose are economical and eco-friendly. For example, silkworms can be used for eating in different regions of the world and also used for industrial purposes. These silkworms can be harvested, semi-domesticated or can be raised in laboratory by using artificial diets. Regarding food safety, there is more research needed on biology and ecology of insects for satisfaction and acceptance of consumers. Those edible insects which breed in farms could be on risk of contamination by microorganisms, chemical impurities, accretion of heavy metals, and the occurrence of allergens and anti-nutrients. Hence there should be regulations and policies to confirm that the growth and use of insects as food and feed does not have any harmful effects on agriculture and human health, also does not produce any contamination in the environment. The main concern is people perception about insect eating is somehow negative, so there should be more research needed to prove insects as sustainable human diet. Evolvement in addressing the societal and scientific concern about insects will increase the industrialization and effective usage of edible insects.

Supplementary material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.24013962

Conflict of interest

The authors declare no conflict of interest.

Data availability

There is not data available for this article.

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SAS: conceptualization, validation, software, data curation, writing original draft, writing review and editing, visualization, supervision, project administration, resources; NN: writing original draft; AME-D: writing original draft; İU: writing original draft; MA: writing original draft; IF: writing review and editing; SS: validation; MAS: validation; SNP: validation; RC-M: validation, funding.

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