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REVIEW ARTICLE

Scarabaeidae as human food – A comprehensive review

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Abstract

Rising global population and sustainable protein demand have sparked interest in unique food sources. Entomophagy, or insect consumption, presents a solution and Scarab beetles, part of the Scarabaeidae family, offer a novel food option. The comprehensive review underscores their potential as human food, with strong nutrition, low environmental impact, and the ability to ease strain on conventional agriculture. Nutritional analysis reveals rich protein content, essential amino acids, vitamins, and minerals. Scarab beetles' beneficial fatty acid profile and healthy fats position them as a superior protein source to traditional livestock. Scarabaeidae excel in feed conversion, emit fewer greenhouse gases, and require minimal land, establishing them as an ecologically sustainable protein source. Cultural attitudes towards insect consumption vary; history exists in some regions while skepticism prevails in others. Highlighting nutritional advantages, organizing outreach, and introducing processed scarab products could enhance acceptance. The review addresses challenges including mass rearing, processing, allergens, and toxins. Evolving insect-based food regulations require cautious consideration. Success depends on multidisciplinary efforts including nutrition, environmental sustainability, cultural openness, and regulatory alignment. Continued research and collaboration are essential to fully unlock Scarabaeidae's potential as a sustainable, nutritious food source for our growing global population.

Keywords

entomophagy – food supply – industrial application – medicinal benefits – nutritional benefits

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1 Introduction

The world's population is projected to increase beyond 9 billion by 2050 with a corresponding increase in the demand for agricultural products (Lee *et al.*, 2021). Population increments not only affect productivity but also the destruction of the ecosystem. Human activities such as the expansion of agricultural lands and rearing of livestock have been found to greatly impact the ecosystem negatively through climate change as a result of greenhouse gas (GHG) emissions thereby affecting food security. This cyclical phenomenon has informed the United Nations (UN) to formulate sustainable development goals (SDGs) to ameliorate the impending danger of population growth (Conover *et al.*, 2019; Ebenebe *et al.*, 2017; Kelemu *et al.*, 2015; Murefu *et al.*, 2019; Raheem *et al.*, 2019a; Żuk-Gołaszewska *et al.*, 2022). Critical to the SDGs are food security challenges with growing concerns over the quantity and quality of food availability. Kelemu *et al.* (2015) and Van Huis (2016) predict an increase in animal protein demand by 2050. Increasing standard of living, urbanization, environmental health and animal welfare issues has influenced the need for alternative protein source (Delvendahl *et al.*, 2022; Patel *et al.*, 2019). With over 2,000 species documented to be edible and consumption predating ancient times (more than 400 milion years ago) (Tang *et al.*, 2019; van Huis, 2022), insects have emanated as the most viable alternative to address global protein demand (Orkusz, 2021; Patel *et al.*, 2019; Tang *et al.*, 2019).

Insects are the most diverse and abundant group of multicellular animals belonging to Phylum Arthropoda already serving as food for over one-third of the world's population mostly in developing countries (Kelemu *et al.*, 2015; Raheem *et al.*, 2019a; Skotnicka *et al.*, 2021). Short life span, poikilothermic nature which makes them efficient users of feed, robust immune system and vicious adaptation to new niches due to their structural body features has accounted for diversity and survival (van Broekhoven *et al.*, 2015). Though usually noted for their notoriety in harming plants and humans (Aidoo *et al.*, 2022a), research suggests high nutritional and health benefits from insect consumption (Nowakowski *et al.*, 2022; Orkusz, 2021). Despite of their numerous benefits, insects have been underutilized as food and feed and have been alluded to limited knowledge about entomophagy and Western countries' inertia to insect consumption due to disgust and unfavourable weather conditions for insects' survival (Grabowski *et al.*, 2020; van Huis, 2022). Hence, Western countries see insects as only good for pollination and biodegradation of waste. However, Rahim *et al.* (2019) were of the view that insect consumption can help alleviate SDG 2 (end hunger, achieve food security and improve nutrition and promote sustainable agriculture), SDG 13 (take urgent actions to combat climate change and its impact) and SDG 15 (to protect, restore and promotes sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification as well as mitigate land degradation and biodiversity loss). Accelerated research has therefore targeted commonly consumed insects albeit unraveling unidentified ones. Prevalent among edible insects are those classified under various orders: Coleoptera, accounting for 31% (beetles); Lepidoptera, representing 18% (caterpillars); Hymenoptera, constituting 14% (bees, wasps, and ants); Orthoptera, comprising 13% (grasshoppers, locusts, and crickets); Hemiptera, making up 10% (cicadas, leaf and plant hoppers, scale insects, and true bugs); Blattodea (specifically, the infraorder Isoptera) at 3% (termites); Odonata, contributing 3% (dragonflies); and Diptera, encompassing 2% (flies) (Skotnicka *et al.*, 2021; van Huis and Arnold, 2013). The diverse nature of Coleoptera group has drawn interest from many researchers to rear them domestically as well as collect them in the wild.

Coleopterans are ubiquitously present on land and in aquatic environments due to their diverse adaptive features. Ramos-Elorduy *et al.* (2009) discovered that, about 6.58% of edible coleopterans in Mexico are aquatic. Generally, the larval stage of coleopterans is most edible with adults largely considered inedible due to the high anti-nutrient content present in their wings, legs and exoskeleton (Adámková *et al.*, 2016; Meyer-Rochow *et al.*, 2021).. Consumption of coleopterans has been centered around larvae of Tenebrionidae and Scarabaeidae in most countries (Moruzzo *et al.*, 2021; Ukoroije and Bobmanuel, 2019). However, scarabaeids are known to be the most abundant coleopterans on earth both for their devastating effect on plants and for consumption as human food (Aidoo *et al.*, 2022a; Bedford, 2013; Bhattacharyya *et al.*, 2018; Ogbalu and Williams, 2015; Park *et al.*, 2020; Song *et al.*, 2017). Scarab beetles offer several advantages and characteristics that make them a promising option for human consumption when compared to other insects. Scarabaeidae provides a source of nutrition and livelihood for people in developing countries especially for the vulnerable (Hlongwane *et al.*, 2020). Women and children in Zimbabwe and Zambia trade *Eulepida mashona* and other scarabaeids to support household income (Murefu *et al.*, 2019; Nyangena *et al.*, 2020). They are notably rich in protein, typically containing approximately 25-50%

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protein by dry weight, which rivals or even surpasses the protein content of other edible insects (Jonathan, 2012; Banjo *et al.*, 2006). Additionally, scarab beetles tend to have lower fat content, making them a lean and nutritious protein source (Banjo *et al.*, 2006) and also contain essential vitamins and minerals like iron, zinc, and B vitamins, contributing to their nutritional value. The Scarabaeidae family is exceptionally diverse, encompassing thousands of species worldwide (Zothansanga, 2021). This diversity opens exciting possibilities for culinary experimentation as different scarab beetle species may offer varying flavors and textures, catering to a wide range of culinary preferences. In some cultures, specific scarab beetle species have a historical tradition of being consumed as a traditional food source, which can contribute to cultural acceptance and familiarity with their consumption (Chakravorty *et al.*, 2011). Furthermore, scarab beetles align with sustainability goals as they require fewer resources, including water, land, and feed, compared to conventional livestock such as cattle. Their eco-friendly profile positions them as a more sustainable protein source (Holter, 2016).

Despite the numerous benefits of these scarabaeids, attention has not been given enough to them with literature on individual species often scanty. This review, therefore, seeks to bring edible scarabaeids into the light while focusing on various important aspects of this group of insect family. We conducted a systematic search for available peer reviewed publications from January 2012 to September 2023 following the PRISMA methodology (Moher *et al.*, 2009). We searched the Scopus, Web of Science, Google Scholar, Sci hub, Semantic Scholar, Science direct and Research Gate databases using the search terms (edible scarabaeid OR scarab beetles) AND (economic importance, nutritional value, anti-nutritional value, processing techniques OR safety concerns) in English. We applied the search terms to the article title, abstract, and keywords to select the relevant articles for this review. A total of 325 articles and reports were identified. We then accessed full texts of the selected articles were then screened for obtaining the needed information. This process identified 169 articles that were relevant for this review.

2 Records of edible Scarabaeidae

The idea of coleopterans being the largest and most diverse group of edible insects (Figure 1) has been documented by many authors (Jongema, 2017; Raheem *et al.*, 2019b; Siddiqui *et al.*, 2023e). However, information about the largest edible group scarabaeids seems to be scanty due in part to the lack of patronage by Western countries. Edible scarabaeids are largely consumed by people in developing countries (Boate and Otayor, 2020; Shanovich *et al.*, 2019). European countries developing aversions to entomophagy due to disgust for insects, suitable environmental conditions, and safety concerns such as allergens, heavy metals, mycotoxin, pesticide residues, anti-nutrient components, microorganisms, and parasites (Imathiu, 2020; Lange and Nakamura, 2021; van Huis, 2016; van Huis, 2022; Siddiqui *et al.*, 2023b). Patronage of insects as food and feed has focused on caterpillars (Lepidoptera), grasshoppers, crickets, locusts (Othoptera) and some coleopterans from the Tenebrionidae family (Melgar-Lalanne *et al.*, 2019; Skotnicka *et al.*, 2021). Scarabaeidae however serves as a reliable alternative protein source and delicacy for developing countries such as India (Bhattacharyya *et al.*, 2018), Ghana (Anankware *et al.*, 2016), Nigeria (Boate and Otayor, 2020; Ebenebe *et al.*, 2017; Ukoroije and Bobmanuel, 2019) Indonesia (Thangjam *et al.*, 2020) and some developed worlds like China (Liu *et al.*, 2012; Tang *et al.*, 2019; Yang *et al.*, 2014).

Distribution and consumption of scarabaeids has been dependent on factors predating colonial era with consumption localized within certain communities (Figure 2). Based on the collected data, we reported 55 species of edible scarabaeids in Tropical African, 9 species in Australian, 6 species in Nearctic, 62 species in Neoptropical, 138 species in Oriental (especially Thailand recorded a total of 114 edible species of scarabaeids) and 18 species in paleaerctic regions of the world. Anankware *et al.* (2016) identified that only one (*Phyllophaga nebulosa* (Harris)) out of nine discovered edible insects in Ghana belonged to the Scarabaeidae with consumption localized predominantly among some tribes in the northern parts of the country. Ukorojie and Bobmanuel (2019) discovered that, people in Bayelsa state (Nigeria) consume *Oryctes owariensis* due to love for the species, nutritional benefit, peer pressure and medicinal purposes. In some Indian tribes, consumption of dung beetles is an additional benefit to other ecological functions such as nutrient recycling, soil aeration, parasite suppression, secondary seed dispersion and bioturbation (Thakkar *et al.*, 2016). However, the number and species of edible Scarabaeidae seems to vary from one ethnic group to the other (Thakkar *et al.*, 2016; Thangjam *et al.*, 2020). Many species of Scarabaeidae have also been reported in other countries but mode of consumption and preparations seems to be similar with little variations due to the

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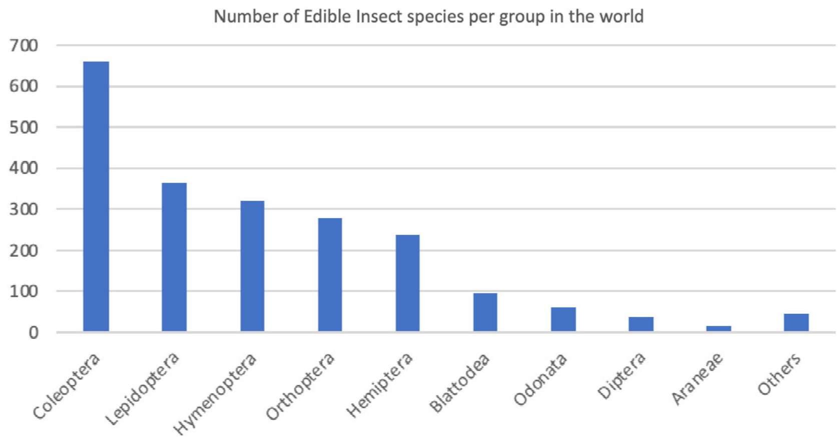

FIGURE 1 Number of edible insects (Jongema, 2017).

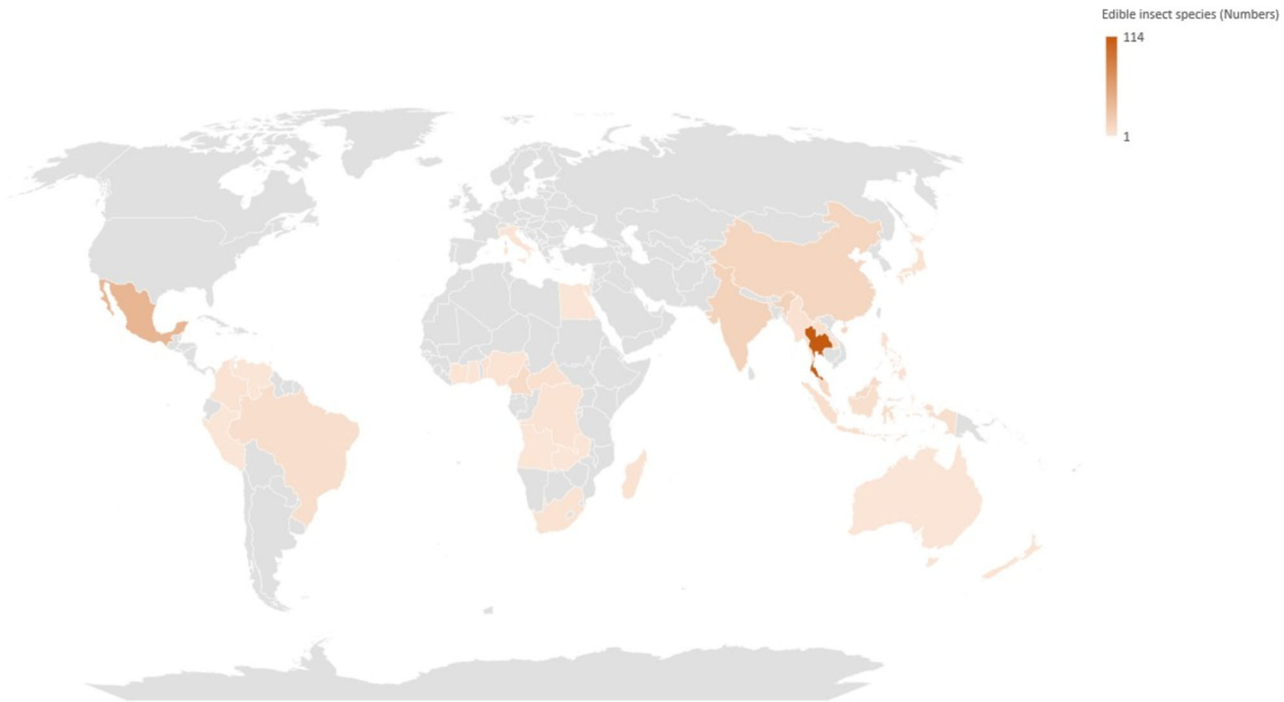

FIGURE 2 Number indication of edible scarabaeidae through heat map. The redness depth responses to the number of edible species in each country.

exclusive cuisines in these countries (Supplementary Table S1). According to Jongema (2017) and other literature (Supplementary Table S1), about 174 species of scarabaeid have been identified as edible spanning over seven different subfamilies (Aphodiinae, Cetoniinae, Dynastiinae, Melolonthiinae, Rutelinae, Scarabaeinae, and Trichiinae).

The consumption of Scarabaeidae in various life stages is influenced by cultural traditions, taste preferences, availability, and nutritional considerations. This flexibility in consumption allows for the utilization of scarab beetles in a wide range of culinary practices and contributes to their appeal as an edible insect in different parts of the world. Though consumed at every stage of their life cycle by different groups around the world, edible scarabaeids are largely consumed at their larval stage, which is known as grubs (Supplementary Table S1) (Garofalo *et al.*, 2019; Ukoroijo and Bobmanuel, 2019). In most cultures, scarabaeids are hunted in the wild but recent interest in animal protein across the globe has projected the call for rearing these insects (Raheem *et al.*, 2019a; Thomas and Kiin-Kabari, 2018; Ukoroije and Bobmanuel, 2019; van Huis, 2022). Most people rear scarabaeids by intentionally inflicting injuries to the host plant for the female insect to lay their eggs while others rely on compost for their rearing (Anankware *et al.*, 2016; Thomas and Kiin-Kabari, 2018; Ukoroije and Bobmanuel, 2019). In most

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countries, scarabaeids are considered snacks as fried or roasted (Ukoroije and Bobmanuel, 2019) however, some consumers prefer their scarabaeids boiled with spices and taken as soup (Anankware *et al.*, 2016; Raheem *et al.*, 2019b). Processing insects into highly shelf stable products are usually done in advanced countries where various species are mixed together as a secret ingredient (Melgar-Lalanne *et al.*, 2019). Kim *et al.* (2019) documented the suitability of yellow mealworms (*Tenebrio molitor*) (Coleoptera: Tenebrionidae) as a food ingredient in bread making, cereal snacks, meat emulsions and emulsion sausages due to the high peptide, fat and ash contents. They however concluded that, further studies need to be done using other insects since resulting products deteriorate with time in their gelling and textural properties. Hence, scarabaeids could be an alternative protein source for these products with high protein content (Rumpold and Schlüter, 2013).

The Korean food regulation authority has recently added the white spotted flower chafer (*Protaetia brevitarsis*) and rhinoceros beetle (*Allomyrina dichotoma*) to their list of edible insects and consciously bred for their food industry (Park *et al.*, 2020; Song *et al.*, 2017). Entomophagy has been long practiced in the Americas like Mexico and Papua New Guinea offering as a major source of livelihood and delicacy. Recently, the detritivore scarabaeids *Cotinus mutabilis* (green fig beetles) have gained popularity in the USA and Mexico (Ramos-Elorduy *et al.*, 2009; Slagle and Davidowitz, 2022). However, consumption of scarabaeids in certain jurisdiction has been hampered by religious beliefs which limit the sharing of recipes (Thakkar *et al.*, 2016; Ukoroije and Bobmanuel, 2019). For instance, majority of people living in Bayelsa state in Nigeria believes adding a few grubs of scarabaeid in the diet of pregnant women aided the delivery of healthy babies (Boate and Otayor, 2020). The importance of edible scarabaeids has therefore been shown to transcend countries, culture, religion and ethnicity with enormous potential yet to be exploited for global food security (Siddiqui *et al.*, 2023c).

3 Bioecology of edible Scarabaeidae

Beetles are known to be more than 25 per cent of all known species in the world (Shen *et al.*, 2019). Their abundance and diversity have been attributed to evolution of sophisticated mechanisms in their reproductive, body structure (Figure 3) and metabolism, feeding and symbiotic relationship with their environment (Aidoo *et al.*, 2022a,b; Conover *et al.*, 2019). Hence, their importance as food and feed is almost always overlooked for the devastating effect they have on plants and humans. Scarabaeids are ubiquitous and can be found in aquatic, rainforest, savanna, hills or mountainous habitats (Conover *et al.*, 2019; Ramos-Elorduy *et al.*, 2009; Salomão *et al.*, 2023). Most scarabaeids are omnivores making them efficient cleaners of the environment through nutrient recycling and removal of GHG (Conover *et al.*, 2019). Herbivores such as *Oryctes* spp., *Holotrichia* spp., *Anomala bengalensis*, *Anisoplia segetum*, and *Popillia japonica* attacks plant tissues (Table 1) irrespective of their stage of development leading to reduction in plant health and overall crop yield (Aido *et al.*, 2022; Althoff and Rice, 2022; Bekircan and Tosun, 2021; Kakulte and Mamlayya, 2022; Thomas and Dimpka, 2021).

The extent of destruction of these phytophagous scarabaeids is dependent on diversity, population fluctuations, percentage of folivore and diet breadths (Kakulte and Mamlayya, 2022). The devastating effects of these herbivores are augmented by the activities of some detritivores who synergistically operate to return nutrients to the soil (Althoff and Rice, 2022). The most common detritivore scarabaeids in the world are found in species of dung beetles (Conover *et al.*, 2019; Salomão *et al.*, 2023; Zhao *et al.*, 2007). The distribution and activity of dung beetles have been found to be influenced by the altitude gradient (Şenyüz *et al.*, 2019), soil humidity, soil texture and forest structure (Conover *et al.*, 2019; Salomão *et al.*, 2023). Conover *et al.* (2019) discovered different groups of dung beetles in the USA and grouped them into dwellers (*Aphodius* spp.), tunnelers (*Onthophagus* spp. *Ateuchus* spp. *Phanaeus* spp. *Dichotomius carolinus*) and Rollers (*Glaphyrocanthon vividris*). Similar groupings were also made by (Salomão *et al.*, 2023) in Colombia and their role in sustaining the rainforest. Generally, the mitigating measures adopted to control harmful pest like chemical spraying and burning of leftover stubbles and straws leads to the destruction of these coprophagous insects in the soil. However, some detritivore scarabaeids have been found to breakdown complex compounds in these chemicals and oils. Shen *et al.* (2019) successfully removed heavy oils containing TPH from soil using *O. rhinoceros* due to the long larval period. They again used the same species to remove other organic pollutants from the environment in 2021 (Shen *et al.*, 2021). Hence, the efficiency of these Scarabaeidae to breakdown waste and host plants depends on the life cycle and associations with microorganisms. Suárez-Moo *et al.* (2020) and Chouaia *et al.* (2019) found dependency between *Copris incertus* Say

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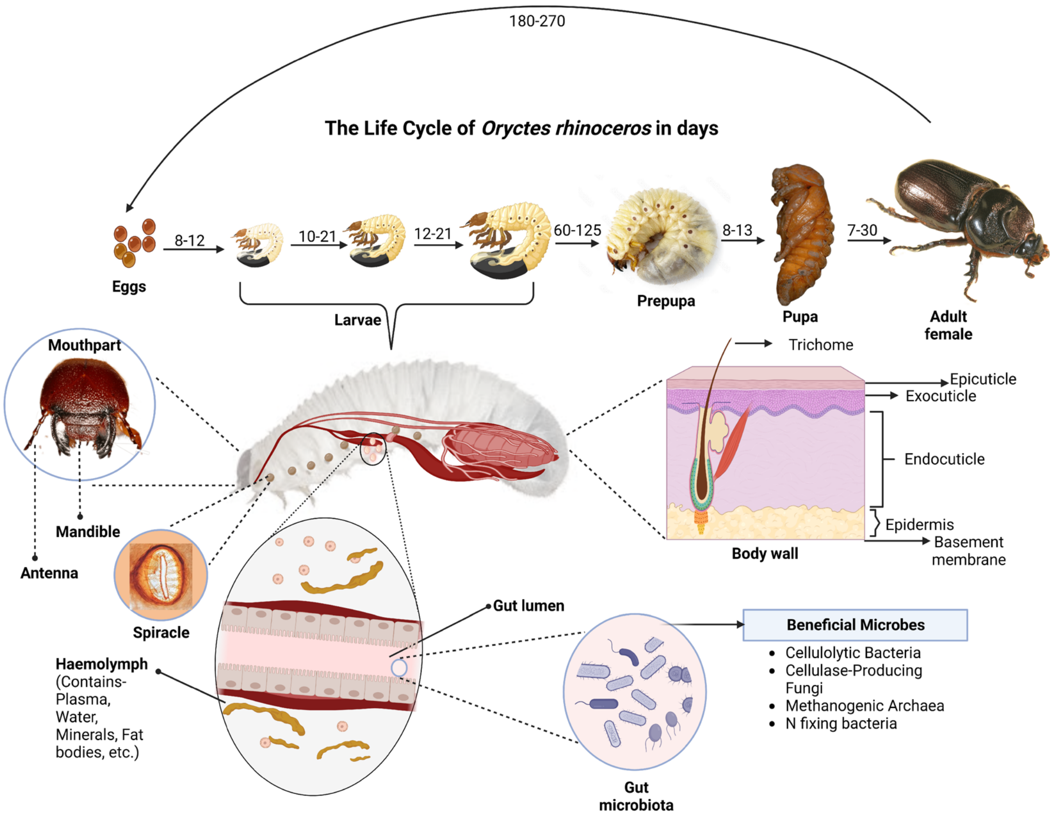

FIGURE 3 A visual guide on metamorphosis and anatomy of *Oryctes rhinocerous*.

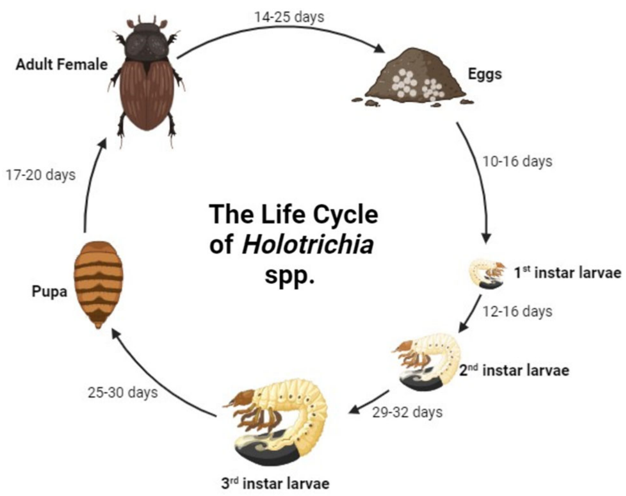

FIGURE 4 Life cycle of *Holotrichia* spp. (Bhawane *et al.*, 2011).

(dung beetle) and *Popillia japonica* Newman, respectively, and their gut microbiota.

The life cycles of scarabaeids are similar, with the majority of them undergoing complete metamorphosis (Figures 4-6) (Aidoo *et al.*, 2022b; Kojima *et al.*, 2019; Jang and Kim 2019; Thomas and Dimkpa, 2021; Siddiqui *et al.*, 2023da). However, the life cycle of scarabaeids is based on the duration and structure of each developmental stage. Generally, adult females find a suitable host and lay eggs after mating with a male counterpart. Mating host and egg laying host may differ for different species. Zhang *et al.* (2019) noted that, adult male and female *H. pararella* fly at sunset to host plant for mating and feeding (7-11 mins) and mated females fly at scotophase to lay eggs in the soil close to the ovipositional host plant. Harada *et al.* (2021) also observed a similar pattern in another *Holotrichia* spp. but noticed that flight performance and mating among insects affect not only egg production but also a strong determinant of individual fitness to avoid predators and disperse seeds or pollen. Thomas and Dimkpa (2021), however, observed a different phenomenon where female *O. owariensis* and *O. boas* either crawl up the same host or fly to a different host plant to lay their eggs. These eggs are hatched after days or weeks depending on the species into young larvae (scarabaeiform) which undergo molting into three (3) different instars before developing into the prepupa and pupa stage. Scarabaeiforms generally have three pairs of true legs on the thorax and a long soft C-shaped abdomen without legs. Most larvae are vicious with huge appetites. Hence, scarabaeiforms are highly nutritious and cause the most devasting damage to plant hosts. Variations in life cycle among Scarabaeidae are dependent on the availability of food and environmental factors (Aidoo *et al.*, 2022a). At the same larval stage, Bhawane *et*

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TABLE 1 Characteristic feeding of some Scarabaeidae in the ecosystem

Species	Primary host plant	Affected plant part and damaging stage	Other host plant	Reference
Anomala bengalensis	Plum Plant (*Syzygium cumini*)	Leaf: Adults	*Cassia fistula*	Kakulte and Mamlayya (2022)
Holotrichia fissa	Plum Plant (*Syzygium cumini*)	Leaf: Adults	*Emblica officinalis*, *Bridelia retusa*, *Careya arborea*, *Zizyphus jujuba*, *Butea monosperma*, *Grewia sp.*, *Terminalia tometosa*, *Terminalia arjuna*	Kakulte and Mamlayy (2022)
Holotrichia karschi	Plum Plant (*Syzygium cumini*)	Leaf: Adults	*Bridelia retusa*, *Acacia auriculiformis*, *Terminalia T. arjuna*, *T. Tomentosa*	Kakulte and Mamlayya (2022)
Holotrichia parallela	*Arachis hypogaea* (Peanut)	Pod: Larva and Adults	Soya beans (*Glycine max*), Sweetpotato (*Ipomea batatas*), glossy privet (*Ligustrum lucidum*) and Siberian elm (*Ulmus pumila*), velvetleaf (*Abutilon theophrasti*), castor bean, (*Ricinus communis*)	Zhang *et al.* (2019)
Oryctes boas	Oil palm (*Elaeis guineensis*) and Date palm (*Phoenix dactylifera*) for adults	Trunk: Adults		Thomas and Dimkpa (2021)
Oryctes monoceros	Raffia palm (*Raphia hookeri*) and oil palm (*Elaeis guineensis*), Coconut (*Cocos nucifera*)	Trunk: Larva and Adults		Thomas and Dimkpa (2021), Ishara *et al.* (2022)
Oryctes owariensis	Raffia palm (*Raphia hookeri*) and oil palm (*Elaeis guineensis*)	Trunk: Adults and larva		Thomas and Dimkpa (2021)
Oryctes rhinoceross	Raffia palm (*Raphia hookeri*) and oil palm (*Elaeis guineensis*), Coconut (*Cocos nucifera*)	Trunk: Adults	Yellow flame (*Peltophorum pterocarpu*) and Mango (*Mangifera spp*)	Thomas and Dimkpa (2021), Ishara *et al.* (2022)
Pentodon quadridens bidentulus	Sugarcane (*Saccharum officianarum*) and Maize (*Zea mays*)	Root: Larva	Rice (*Oryza sativa*) and tobacco (*Nicotiana tabacum*)	Jang and Kim (2019)

al. (2011), observed 12-16 days in the 1st larval instar *Holotrichia* spp., 29-32 days in 2nd instar and 25-30 days in the 3rd instar (Figure 4). Saldanha *et al.* (2020) observed that, *Cyclocephala putrida* Burmeister used 16 days to molt from 1st instar to 2nd instar before using 48 days to move into the 3rd instar and finally spending 165 days before the pupa stage (Figure 5). Aidoo *et al.* (2022a) however reported a much variable larval duration in *O. rhinoceros* (Linnaeus) (Figure 6). This could perhaps explain the high destructive ability of *O. rhinoceros* in coconut and date palms. Similar variations in the pupa stage of development have been reported in various species of Scarabaeidae with others passing through a pre-pupal stage before attaining pupa. The pupa subsequently form cocoon around itself for protection and feeding till the young adult insect emerges

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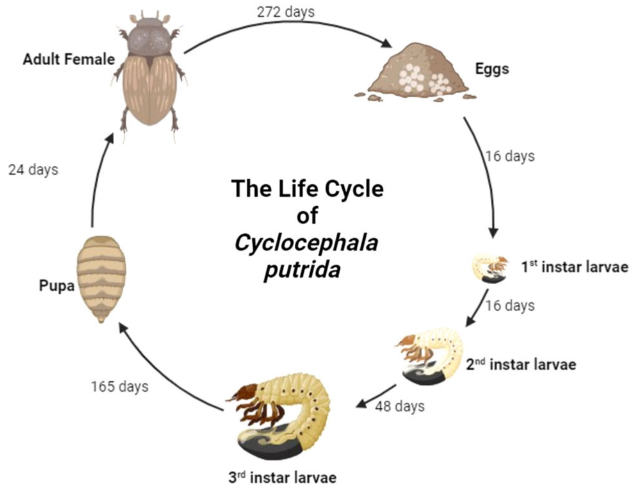

FIGURE 5 Life cycle of *Cyclocephala putrida* (Saldanha *et al.*, 2020).

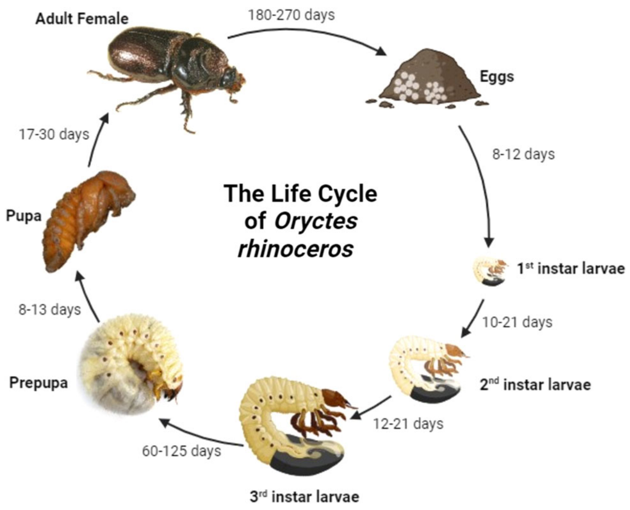

FIGURE 6 Life cycle of *Oryctes rhinoceros* (Aidoo *et al.*, 2022a).

and fly out to start a new cycle (Shen *et al.*, 2019; Thomas and Dimkpa, 2021). As a result of egg laying most female insects show female-baised sexual size dimorphism to enhance fecundity. Kojima *et al.* (2019) working on *Trypoxylus dichotomus* Linnaeus discovered that, this variability is also affected by body size plasticity.

The primary host or the food substrates affect various aspects of grub development and fitness, including nutritional quality, growth rate, and larval and pupal development. As reported by Anaduaka *et al.* (2021), *O. rhinocerous* larvae obtained from the *Raffia* palms had 26.17 ± 2.061 per cent moisture, 10.00 ± 0.012 per cent ash, 34.76 ± 0.442 per cent crude protein, 10.00 ± 0.013 per cent crude lipid, 8.70 ± 0.701 per cent crude fibre and 10.37 ± 1.732 per cent carbohydrate. However, the grubs obtained from oil palm trees reported 5.42 ± 0.11 per cent moisture, 11.83 ± 0.14 per cent ash, 52.00 ± 1.00 per cent crude protein, 10.84 ± 0.31 per cent crude lipid, 17.94 ± 0.20 per cent crude fibre and 1.97 ± 0.01 per cent carbohydrate (Omotoso, 2015). Shafiei *et al.* (2001) found that *O. taurus* larvae respond to food deprivation by reducing the instar and pupation length, leading to early eclosion of small adults (Shafiei *et al.* 2001). Larvae allowed to feed longer on the substrate produced healthier pupae. Moczek (1999) demonstrated that the size of offspring of dung beetles is determined by the quality and quantity of dung provided to the parents rather than by genetics. Horse dung was shown to be a higher quality resource for developing larvae, with relatively small amounts being sufficient to support development. In contrast, a diet of cattle dung required roughly a 50-75% larger brood ball mass to yield comparable adult body size (Moczek, 1999). Therefore, the overall life cycle of Scarabaeidae can be said to be influenced by both the genetic, environmental and feeding substrate conditions under which it survives with environmental and feeding substrate conditions sometimes altering the body size and duration of each developmental stage even within the same species.

4 Economic importance of Scarabaeidae

The economic importance of scarab beetles is multifaceted. Given the dual nature of insects as both beneficial and harmful, it is crucial to raise awareness and create an environment that allows us to harness the importance of insects in achieving sustainable development goals (Figure 7). On the negative side, certain scarab beetle species can be agricultural pests (Aidoo *et al.*, 2023), serve as disease vectors causing crop damage, damage stored grains and household furniture and even produce poisonous substances (Chimela *et al.*, 2021). The detrimental impact of Scarabaeidae on crops has resulted in significant economic losses in various countries. For example, Paudel *et al.* (2021) reported economic losses of US $159.4 million, US $299.3 million, and US $2,853.7 million in the coconut industries of India, Indonesia, and Malaysia, respectively, due to *Oryctes rhinoceros*. Similarly, in the Solomon Islands, the same species caused approximately US $17 million in damages to the coconut industry by reducing crop yields and affecting tourism. In the United States, *P. japonica* caused extensive destruction of ornamental plants, residential turf, and fruit crops, such as raspberries. This has led to investments in insecticides, high tunnels, netting, plastic coverings, and biological control methods to manage and eliminate these pests (Burkness *et al.*, 2022). Novel but expensive methods like encap-

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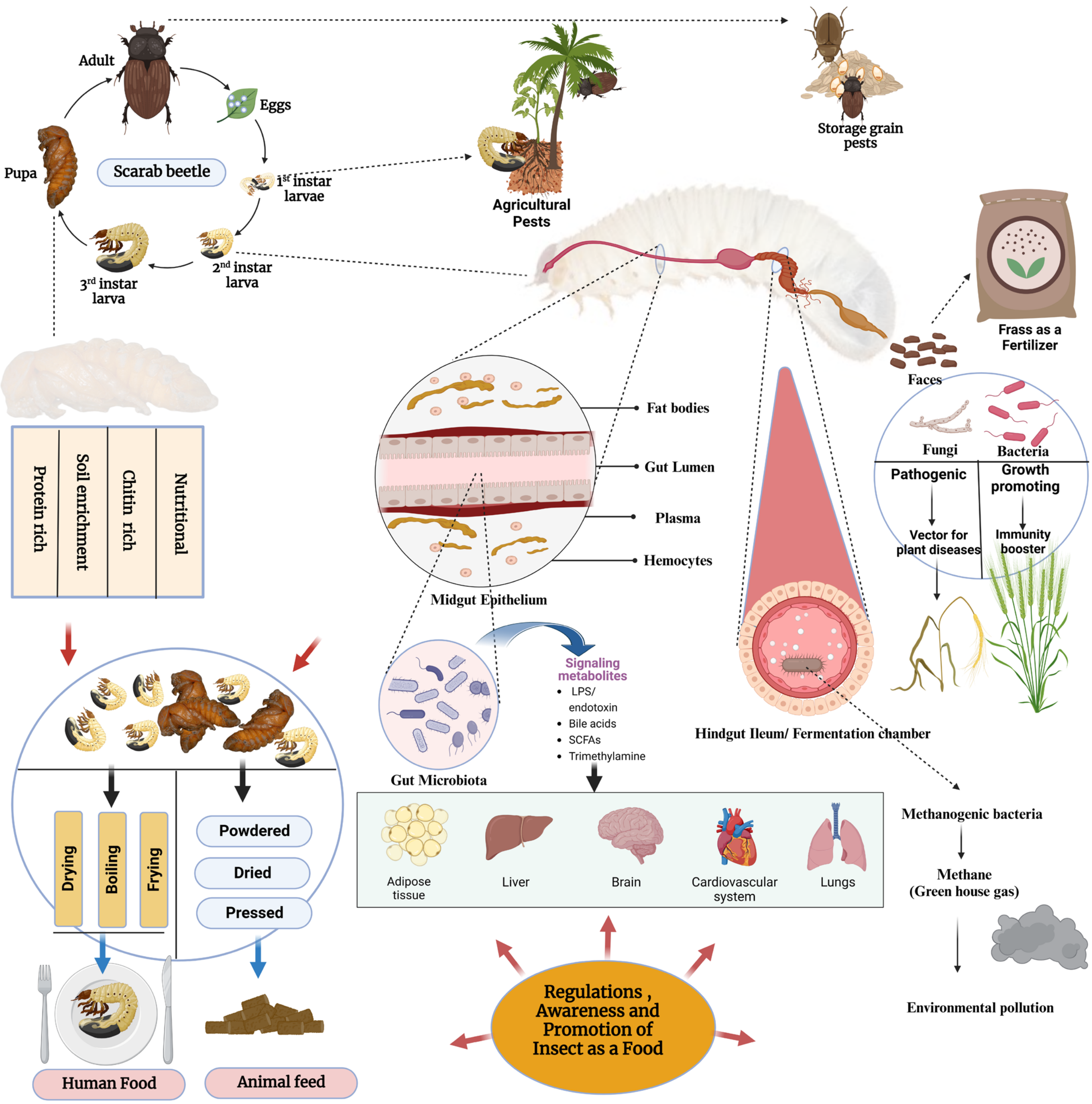

FIGURE 7 The multifaceted impact of edible scarabaeids on national economy: A schematic analysis of food, feed, waste production, and environmental regulation.

sulated pesticides and *Bacillus thuringiensis* have been used to manage *H. parallela*, a species that can reduce peanut yields by 20-30% (Yang *et al.*, 2014; Zhang *et al.*, 2019). Interestingly, consuming some of these pests could potentially contribute to managing their effects on crop yields.

On the positive side, some species such as dung beetles, contribute to improved soil fertility and nutrient cycling, benefiting agriculture and ecosystems (Beynon *et al.*, 2015). Scarab beetles also play a role in biodiversity and ecotourism, supporting diverse species and offering economic opportunities through nature-based tourism (Zothansanga, 2021). In research and biotechnology, they serve as valuable model organisms, advancing scientific knowledge and applications (Takov *et al.*, 2022). Additionally, their potential use as a food source and in animal feed production presents economic prospects (Nowakowski *et al.*, 2022; Orkusz, 2021). In some parts of the world, Scarabaeidae, such as *O. monoceros*, *O. rhinoceros*, *O. owariensis*, and *Phyllophaga nebulosa* serve as a crucial source of nourishment, especially in underdeveloped regions like Africa and certain Asian countries. This is particularly significant because a significant proportion of undernourished children are con-

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centrated in these areas, with south Saharan Africa contributing about a third of undernourished children globally (Matandirotya *et al.*, 2022). However, there are challenges in the trade and consumption of Scarabaeidae. In rural markets, the handling techniques are often unhygienic, presentation is lacking, and the variety of insect products is limited. Conversely, in urban markets, where incomes are higher, the few insect products available are sold at relatively high prices (Grabowski *et al.*, 2020; Mandirotya *et al.*, 2022). Due to the unconventional nature of insect trade in these communities, economic data is scarce and rarely reported.

In many countries, insect consumption is often associated with poverty and is commonly referred to as "poor man's food." Consequently, insect consumption is prevalent in rural communities where a majority of people live below the poverty line. In these communities, Scarabaeidae, among other insects, have long been a source of livelihood for women and children (Anankware *et al.*, 2016; Ebenebe *et al.*, 2017; Mandirotya *et al.*, 2022; Ukoroije and Bobmanuel, 2019). In many cases, they serve as a temporary source of nourishment for those engaged in farming activities (Anankware *et al.*, 2016). Importantly, the edibility of Scarabaeidae insects has been found to be quite high, with a reported edibility rate of 100% if eaten whole and 80% if the guts and legs are discarded. This compares favorably to chicken (55%) and beef (40%) (Grabowski *et al.*, 2020).

While scarabaeidae products are less common in Western markets, they play a role in traditional diets in some parts of Africa, Asia, and Latin America, with availability and acceptance varying by region and cultural preferences (Siddiqui *et al.*, 2023f). Processed Scarabaeidae products can take various forms, including fresh, semi-finished, and derivative products. Scarabaeidae grubs are often consumed in their fresh form. They can be prepared by cooking methods such as roasting, frying, or boiling and are typically eaten as whole insects or used as ingredients in various dishes (Ramos-Elorduy and Pino, 2006; Megido *et al.*, 2018). Drying scarabaeidae grubs extends their shelf life, making them suitable for snacks, rehydration, or grinding into a powder for diverse food products (Ramos-Elorduy and Pino, 2006). The processing of grubs into flour or powder allows their incorporation into baked goods, protein bars, and protein-enriched foods (Rumpold and Schlüter, 2013). Moreover, these grubs can be processed to yield protein concentrates or isolates, ideal for use in protein supplements, shakes, nutritional bars, and sports nutrition products (Megido *et al.*, 2018).

The economic importance of Scarabaeidae extends to the livestock industry, where reports suggest that livestock fed on insect-based feed perform better than those on standard feed (Hodge, 2022; van Huis, 2022). In contrast to standard cereal-based feed, which is often imported and can be costly, raising or harvesting insects for use as feed for poultry, pigs, fish, and exotic pets, such as reptiles, requires limited capital investment (Hodge, 2022). While there are concerns about the downsides of rearing insects for feed, such as the presence of exoskeleton fragments, exuviae, and harmful microorganisms (Poveda, 2021; Smitt and de Vries, 2020). Many entrepreneurs have found valuable uses for these insect-related materials. For instance, oil palm weevils, which infest felled oil palm trees and contribute to their decay, make the wood suitable for mushroom cultivation or growth in the wild (Sudirman *et al.*, 2022). Borkent and Hodge (2021) have also highlighted the use of waste materials generated from insect farming, including exoskeletons and other by-products, for improving soil structure, enhancing water retention, fostering a healthy soil microbiome, increasing plant resistance to abiotic stress, and protecting against pathogens. This approach requires fewer resources and contributes to improved crop yields while promoting sustainable land use practices. Furthermore, from an environmental perspective, the organic waste generated from various sources is diverted into insect farming systems, thereby reducing the waste disposed of in landfills. This diversion not only helps manage waste more sustainably but also reduces the potential for increased greenhouse gas emissions associated with landfill sites (Hodge, 2023).

5 Nutritional composition of Scarabs

Despite the numerous benefits accrued to entomophagy, the most advanced argument has been its nutritional and health benefits (Figure 8) (Köhler *et al.*, 2019; Rumpold and Schlüter, 2013). This in part is attributed the growing concerns of malnutrition (obesity, protein energy malnutrition and micronutrient deficiency) especially in developing countries and continents. With SDG 2 aiming to end hunger, achieve food security and improve nutrition and promote sustainable agriculture, the insect is not viewed as an important vehicle for achieving this objective. In Asia alone, about 17.9 million children under 5 years are saddled with stunting whiles 5.4 million children experience wasting (Köhler *et al.*, 2019). Insect falls within a group of cheaper tra-

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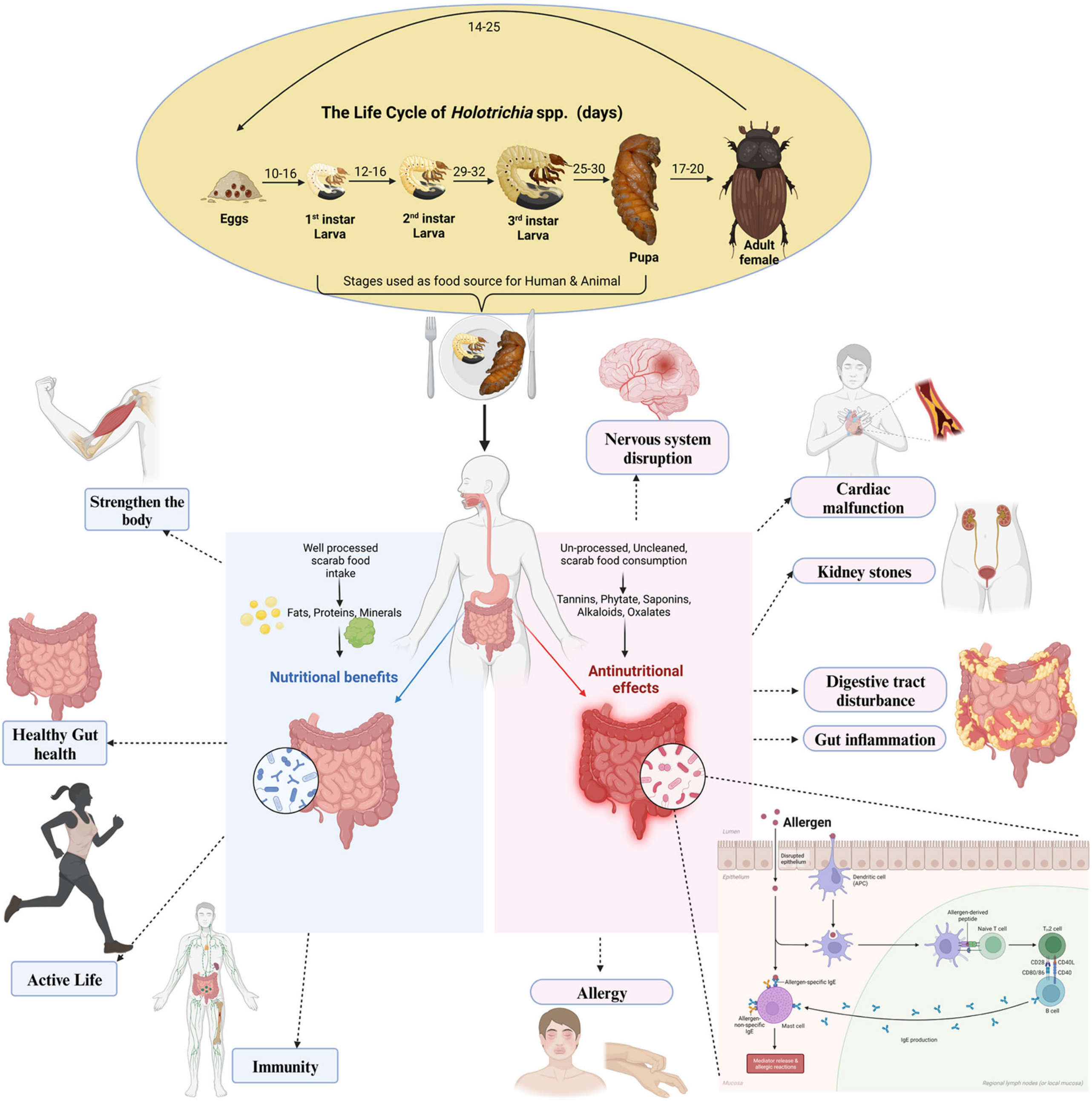

FIGURE 8 Functional properties of scarabaeidae as human food.

ditionally underexploited foods capable of meeting the daily dietary requirements of humans. Several reports have elucidated the rich nutrients, such as proteins, calories, minerals, fats and vitamins, found in insects (Figure 9) (Idowu *et al.*, 2019; Köhler *et al.*, 2019; Ojha *et al.*, 2021; Raheem *et al.*, 2019b).

In most cases, these nutrients are comparable or higher than that found in well-known foods such as meat and vegetables. For example, Köhler *et al.* (2019) documented that insect protein to range between 20% to 70% on a dry weight basis which was significantly higher than that of pork (21%), cow milk (28%) and egg (49%). Rumpold and Schlüter (2013) also suggested comparable energy content in edible insects to all meat with the exception of pork. However, these nutritional contents seem to vary according to species, preparation for consumption, preparation for nutrient analysis, developmental stage of the insects, diet of insects and geographical location (Kulma, 2020; Ojha *et al.*, 2021). Owing to their diverse nature, coleopterans have become one interesting insect order critical to alleviating malnutrition and other nutrition-related challenges in the world. Special attention has been reserved for Scarabaeidae insects due to the importance of their host plants to the national economy of most developing nations. *O. monoceros* and *O. rhinoceros* are well-known

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	Protein (%)	Fat (%)	Fibre (%)	NFE (Carbohydrates) (%)	Ash (%)	Energy content [Kcal/100 g]	Tannins (mg/g)	Oxalate (mg/g)	Ca	K	Mg	Fe	Zn	Mn	Cu
Copris nevinsoni	54.43	13.61	15.15	7.63	9.18										
Holotrichia parallela	70.57	3.76	10.47	6.04	5.53				14.15	138.87	20.65	2.81	1.54	0.68	0.72
Holotrichia spp.	51.74	5.41	19.31	11.2	12.34						6.62	2.31			
Oryctes boas (larvae)	26	1.5	3.4	38.5	1.5		0.04	0.54	45.68	19.55	7.12	1.47	2.12	0.39	0.11
Oryctes monoceros (larvae)	36.67	18.37	12.89	7.46	2.73	21.9	0.05	0.18	9.58	72.78	266.47	15.85	4.87	5.67	0.76
Oryctes owariensis (dried larvae)	36.86	12.46	1.75	46.52	2.44		5.39	1.28	46.39	84.37	270.91	18.68	6.95	5.92	0.85
Oryctes owariensis (larva)	41.75	15.57	2.8	35.15	4.73		5.78	1.56	48.57	49.62	58.73	5.87	3.68	1.08	
Oryctes rhinoceros (adults)	74.18	9.55	3.69	2.76	5.29	1661.33	4.22	1.19	35.48	67.54	71.54	6.35	4.55	1.25	
Oryctes rhinoceros (larvae)	70.76	7.47	5.44	7.01	8.29	1598.48	5.6	1.31	43.37	0.2		4.94			
Oryctes rhinoceros (pupae)	65.34	20.21	2.24	4.28	3.17	1931.31	6.75	1.33	34.29	45.77	56.55	5.54	4.55	1.02	
Phyllophaga sp. (larvae)	42.52	5.72	12.3	15.36	24.1	282.32			0.06	1.28	0.19		166.13	19.83	21.87
Phyllophaga sp. (adults)	47.41	18.81	4.17	15.92	13.69	282.74			0.05	1.3	0.19		170.66	31	22.66

Red – low amount of nutrient
Green - Rich in nutrient

FIGURE 9 Nutritional properties of different scarabaeid species.

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pests of oil palm and coconut (Aidoo *et al.*, 2022a,b) which are major crops driving developing countries like Malaysia, Indonesia, Cameroon and Nigeria (Woittez *et al.*, 2017). Therefore, comparative studies on the nutritional profile of some noted scarabaeid insects have been carried out to broaden the knowledge base of edible insects and inform policy making.

Proximate composition of Scarabaeidae

Like all insects, scarabaeids are predominantly rich in proteins ranging between 21% to 74% on a dry weight basis (Table 2) or 7% to 48% on a fresh weight basis (Churchward-Venne *et al.*, 2017). Proteins are macromolecules made up of smaller subunits of amino acids capable of repairing worn-out animal tissues. Comparing protein content of different species of Scarabaeidae and termite, Idowu *et al.* (2019), noted that, *O. boas* and *O. monoceros* had lower protein content than the termite but were within acceptable limits capable of providing the daily recommended protein needs of humans (23-56 g). The higher protein content of termite was attributed to the overfeeding and nourishment by worker termites before embarking on nuptial flight. *O. monoceros* were however richer in protein content with Rumpold and Schlüter (2013) also reporting lower protein contents in *O. boas* in earlier research. Yang *et al.* (2014) also observed a higher protein content in *H. parallela* (24%) than silkworm. They found that, the 70.57 g/100 g of protein in *H. parallela* was comparable to beef and pork (40-75 g/100 g) but was higher than most Scarabaeidae. There are conflicting reports regarding the protein content of the various development stages. Whiles others report a higher larval protein content than in later stages of development, Omotoso (2015), discovered a higher protein content in the adult stage of *O. rhinoceros* (74.18%) than in the larval and pupa stage. However, there is a general consensus that, processing scararabaeidae reduces the protein content (Ukoroije and Bobmanuel, 2019).

Scarabaeidae are also noted for their high mineral content making them suitable food sources for high endemic micronutrient deficiency communities. Individual minerals play different roles in the human system with minerals such as potassium (K), sodium (Na) playing critical roles in regulating body fluids and balancing body fluid ions (Idowu *et al.*, 2019). About 12 g of *O. monoceros* is enough to provide the recommended daily potassium intake compared to 9 g of termites (Idowu *et al.*, 2019). Manning *et al.* (2023) concluded that environment affected the mineral composition of *Phyllophaga* sp. in Canada. While potassium and sodium are also important for heart and muscle functions, Iron (Fe) and calcium (Ca) blood haemoglobin production and bone formation, respectively (Idowu *et al.*, 2019). While (Köhler *et al.*, 2019) found the effect of selling points (street vending and supermarket) on mineral content of scarabeid beetles, Yang *et al.* (2014) reported higher zinc (Zn) content in *H. parallela* than silkworm pupa and Idowu *et al.* (2019) concluding that *O. monoceros* possess higher magnesium (Mg) and sodium (Na) content than termites. Mineral content also varies within the same species of Scarabaeidae (Idowu *et al.*, 2019; Manning *et al.*, 2023 Rumpold and Schlüter, 2013). Ukorojie and Bobmanuel (2019) also indicated that, processing destroyed most minerals with the exception of sodium (Na). Comparing to other known vegetables, *O. owariense* and *O. rhinoceros* have been found to be higher in Mg than Amaranthus, Aubergine, radish and okra. *O. owarienses* also possess higher Fe content than most leafy vegetables and hence can help mitigate anaemia incidence in vulnerable societies like sub-Saharan Africa. Unlike all, some minerals are known to be extremely toxic to human systems and are mostly referred to as heavy metals. Köhler *et al.* (2019) found trace elements of arsenic (Ar), cadmium (Cd), lead (Pb) and mercury (Hg) in both street and supermarket vented *H. parallela* but were below the minimum threshold levels to cause harm to humans. However, most scarabeid insects have been found to have fewer antinutrients than that in legumes, nuts, tubers and grains. Hence, consumption of scarabeid insects is healthier in terms of nutrient absorption than in most vegetables and medicinal plants.

Carbohydrates and fiber are generally low in insects with chitin constituting the majority of these macronutrients (Aguilera *et al.*, 2021; Ojha *et al.*, 2021; Yang *et al.*, 2014). Chitin consists of a non-digestible polysaccharide (N-acetylglucosamine) forming a large chunk of insect exoskeleton (Aguilera *et al.*, 2021). Hence, reports on the carbohydrate content of most insects have conflicting which could be attributed to the method used in evaluating the content. While some researchers measure the total carbohydrate content, others choose to eliminate the chitin content before testing. However, processing tends to reduce the carbohydrate content of *Oryctes* spp. (Ukoroije *et al.*, 2019). Though chitin is reported to have antioxidant, antitumor and antimicrobial properties, allergic reactions have also been reported (Ohja *et al.*, 2021). Insects have trace elements of antinutrients such as saponins, oxalate, phytate, tannins and alkaloids (Imathin, 2020; Omotoso, 2018; Ukoroije *et al.*, 2019) which prevents the absorption of essential nutrients as

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TABLE 2 Proximate composition of some Scarabaeidae insects

Edible insects (based on dry matter)	Protein (%)	Fat (%)	Fiber (%)	NFE (Carbohydrate) (%)	Ash (%)	Energy content [Kcal/ 100 g]	Country	Reference
Copris nevinsoni	54.43	13.61	15.15	7.63	9.18		Thailand	Rumpold and Schlüter (2013)
Holotrichia parallela	70.57	3.76	10.47	6.04	5.53		China	Yang *et al.* (2014)
Holotrichia spp.	51.74	5.41	19.31	11.20	12.34		Thailand	Rumpold and Schlüter (2013)
Oryctes boas (larvae)	26.00	1.50	3.40	38.50	1.50		Nigeria	Rumpold and Schlüter (2013)
Oryctes boas (larvae)	30.64	18.99	6.97	22.88	5.75	15.57	Nigeria	Idowu *et al.* (2019)
Oryctes monoceros (larvae)	36.67	18.37	12.89	7.46	2.73	21.90	Nigeria	Idowu *et al.* (2019)
Oryctes owariensis (dried larvae)	36.86	12.46	1.75	46.52	2.44		Nigeria	Ukoroije and Bobmanuel (2019)
Oryctes owariensis (larva)	41.75	15.57	2.80	35.15	4.73		Nigeria	Ukoroije and Bobmanuel (2019)
Oryctes rhinoceros (adults)	74.18	9.55	3.69	2.76	5.29	1661.33	Nigeria	Omotoso (2018)
Oryctes rhinoceros (larvae)	70.76	7.47	5.44	7.01	8.29	1598.48	Nigeria	Omotoso (2018)
Oryctes rhinoceros (pupae)	65.34	20.21	2.24	4.28	3.17	1931.31	Nigeria	Omotoso (2018)
Oryctes rhinoceros (larvae)	57.81	0.73	1.40	24.51	15.56		Nigeria	Rumpold and Schlüter (2013)
Phyllophaga sp. (larvae)	42.52	5.72	12.30	15.36	24.10	282.32	Mexico	Rumpold and Schlüter (2013)
Phyllophaga sp. (adults)	47.41	18.81	4.17	15.92	13.69	282.74	Mexico	Rumpold and Schlüter (2013)
Phyllophaga spp. (adults)	39.40	17.70	7.70	38.40	4.50	455.00	Spain	Aguilera *et al.* (2021)

well as serving as allergens (Idowu *et al.*, 2019). However, most researchers argue the insignificance of the quantities to human health.

Amino acid composition of Scarabaeidae

The quality of proteins and their functions are dependent on its amino acid content. Out of the 20 amino acids known, 18 of them have been found in edible insects of which 9 are among the essential amino acids (amino acids that cannot be synthesized by humans) (Köhler *et al.*, 2019). Therefore, their amino acid components are comparable to soya beans and superior to vegetable proteins but inferior to commercial livestock (Kulma *et al.*, 2020). While some researchers postulate location affects the essential amino acid content of edible insects (Kulma *et al.*, 2020), others rarely witness any change (Gere *et al.*, 2017). Generally, most Scarabaeidae seem to be low in methionine and cysteine (Table 3) but compare favourably with casein, beef, egg white and wheat flour (Ojha *et al.*, 2021). Like most essential nutrient, amino acids can vary based on some biological factors such as breeding or rearing, maturity, feed, and gut content or abiotic factors such as mode of preparation and cooking method, mode of preparation for test

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analysis and geographical location (Köhler *et al.*, 2019). Hence the amino acid content difference observed in *H. pararella* Yang *et al.* (2014) and Rumpold and Schlüter (2013) (Table 3) is justified. Due to the lack of focus on edible Scarabaeidae, limited information on their amino acid composition has been provided in literature.

Fatty acid composition of Scarabaeidae

Fat constitutes the second largest macronutrient in most edible insects and varies from 7 g/100 g to 77 g/100 g (Yang *et al.*, 2014). Known for their role in food palatability, fats play a critical role in biological functions and nutrient transport in animals (Idowu *et al.*, 2019). The quality of insect fat is determined by their fatty acid composition which is found to vary within and among species depending on feed and stage of development (Kulma *et al.*, 2019; Rumpold and Schlüter, 2013). Omotoso (2018) reported a higher fat content in scarabeid beetle's pupa and adults than the larva. Resolution is yet to be made on the best type of fatty acids with favorable arguments raised for both saturated and unsaturated fatty acids. Fortunately, Scarabaeidae insects have been found to be rich in both types of fatty acids. Yang *et al.* (2014) identified high content of palmitic acid (saturated fatty acid), Oleic acid (monounsaturated fatty acid) and linoleic acids (polyunsaturated fatty acids) with trace amounts of other variable fatty acids in adult *H. parallela* (Table 4). Like the protein content, Idowu *et al.* (2019) discovered a higher fat content in termites than in *O. boas* and *O. monoceros*. Most coleopterans have a fairly balanced composition of saturated monounsaturated, polyunsaturated fatty acids (Rumpold and Schlüter, 2013), which is comparable to that of edible palm oil (Table 4). *Onthophagus mouhoti* has been found to be containing high amount of oleic acid than palm oil, soyabean oil, pork lard, beef tallow and chicken fat (Table 4), while *Oryctes owariensis* is richer in linoleic acid than palm oil, pork lard, beef tallow and chicken fat (Table 4). These essential fatty acids make these insects a richer source of polyusaturated fatty acids than most conventional meat products. However, the quality of fat can also be measured by its atherogenicity (determinants of atherosclerosis) and thrombogenicity (determinants of blood clotting) which are crucial to predicting cardiovascular risks in humans (Acay *et al.*, 2014; Kulma *et al.*, 2020). These fatty acid properties are also comparable to pork lard, chicken fat and margarine (Kulma *et al.*, 2019; Mlcek *et al.*, 2019). Variations exist even within the same scarabeid species (Table 4) and probably are attributed to reasons alluded to general insect fat content.

Mineral composition of Scarabaeidae

Numerous studies underscore the valuable role of scarabaeids as robust mineral sources (Table 5), meeting essential nutrient requirements in specific developing regions (Yang *et al.*, 2014) Scarabaeids species such as *Holotrichia parallela* (Yang et al., 2014), *Oryctes boas* larvae (Rumpold and Schlüter, 2013; Idowu *et al.*, 2019), *Oryctes monoceros* larvae (Idowu *et al.*, 2019), *Oryctes owariensis* larvae (Ukoroije and Bobmanuel, 2019), *Oryctes rhinoceros* adults, larvae and pupae (Omotoso, 2018), and *Phyllophaga* sp. (Manning *et al.*, 2023) emerge as a reservoir of vital minerals, exemplified by the range of calcium (0.04-48.57 mg/100 g), potassium (0.2-138.87 mg/100 g), magnesium (0.17-270.91 mg/100 g), potassium (0.69-130.2 mg/100 g), sodium (0.16-129.1 mg/100 g), iron (1.47-15.85 mg/100 g), zinc (1.54-179.95 mg/100 g), manganese (0.39-36.03 mg/100 g), and copper (0.11-22.66 mg/100 g) they contain (Manning *et al.*, 2023; Idowu *et al.*, 2019; Omotoso, 2018; Rumpold and Schlüter, 2013). Notably, these mineral concentrations often rival or even surpass those in widely preferred vegetables such as amaranthus, okra, aubergine, and radishes. Comparatively, the latter showcase magnesium at 14.2-25.8 mg/100 g, sodium at 10.7-53.6 mg/100 g, iron at 10.68-11.64 mg/100 g, zinc at 0.28-0.87 mg/100 g, and copper at 7.42-9.32 mg/100 g (Rehman *et al.*, 2014). It's pertinent to acknowledge that the mineral composition within these scarabaeids can fluctuate due to species differentiation, developmental stages, and the substrate upon which they feed (Manning *et al.*, 2023; Idowu *et al.*, 2019; Omotoso, 2018; Rumpold and Schlüter, 2013). This comprehensive understanding underscores their potential significance in providing dietary minerals in diverse contexts.

Anti-nutritional composition of Scarabaeidae

The nutritional profile of scarabaeidae beetles includes not only essential nutrients but also certain anti-nutritional components that warrant consideration (Obeng *et al.*, 2020). These factors includes oxalates with potential mineral-binding effects (Brennan *et al.*, 2018), tannins that could reduce protein bioavailability (Farahat *et al.*, 2019), could affect the overall nutritional value of scarab beetles as a potential food source, phytate which could cause potential health implications due to its interactions with certain minerals and its impact on nutrient absorption, saponins that could disrupt cell membranes in the digestive tract, leading to gastrointestinal disturbances (Schlemmer *et al.*, 2009) and some alkaloids that are toxic and can cause nervous system disruption, cardiovascular effects, and poten-

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TABLE 3 Amino acid composition of some Scarabaeidae compared to other important protein sources

Edible insects [mg/g protein]	His	Ile	Leu	Lys	Met	Cys	Met+ Cys	Phe	Tyr	Phe+ Tyr	Thr	Trp	Val	Arg	Ser	Pro	Ala	Gly	Glu A	Reference
Holotrichia parallela	1.41	2.92	4.38	3.59			1.87			3.74	1.97	0.68	3.41	2.40	2.40	1.90	3.66	4.81	6.92	Yang *et al.* (2014)
Holotrichia spp.	16.10	32.10	51.80	18.80			44.60			49.30	26.90	27.10	29.30	32.30	31.30	47.00	58.30	52.80	97.60	Rumpold and Schlüter (2013)
Oryctes rhinoceros (larvae)	38.20	39.80	53.00	44.20	19.40	20.20	39.60	46.10	30.90	77.00	33.40		35.00	81.60	37.00	50.10	52.50	47.20	154.60	Rumpold and Schlüter (2013)
Scarab beetle	25.20	44.30	73.30	53.60			15.60			31.80	37.00	16.30	64.70							Ojha *et al.* (2021)
Casein	32.00	54.00	95.00	85.00			35.00			111.00	42.00	14.00	63.00							Ojha *et al.* (2021)
Beef	32.00	42.00	78.00	79.00			33.00			70.00	42.00	10.00	45.00							Ojha *et al.* (2021)
Egg white	23.00	53.00	88.00	70.00			66.00			91.00	47.00	15.00	68.00							Ojha *et al.* (2021)
Wheat flour	22.00	33.00	69.00	27.00			39.00			78.00	29.00	11.00	43.00							Ojha *et al.* (2021)
Soybean	25.00	47.00	85.00	63.00			24.00			97.00	38.00	11.00	49.00							Ojha *et al.* (2021)
1985 FAO/WHO/UNU (mg/g protein)	15.00	30.00	59.00	45.00			22.00			38.00	23.00	6.00	39.00							Ojha *et al.* (2021)
(mg/kg body mass/day)	10.00	20.00	39.00	30.00			14.00			25.00	15.00		26.00							Ojha *et al.* (2021)

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TABLE 4 Fatty acid composition of some Scarabaeidae insect species

Fatty acid composition (% fatty acid) / Species	Myristic (C14:0)	Pentadecanoic acid (C15:0)	Palmitic (C16:0)	Stearic (C18:0)	Palmitoleic acid (C16:1) n7	Oleic acid (C18:1) n9	Linoleic (C18:2) n6	Alpha Linolenic acid (C18:3) n3	Gamma Linolenic acid (C18:3) n6	Arachidic acid (C20:0)	Eicosenoic acid (C20:1)	Eicosatrienoic acid (C20:3) n6	Eicosatetraenoic acid (C20:4) n6	Eicosapentaenoic acid (C20:5)	Behenic acid (C22:0)	Lignoceric acid (C24:0)	Reference
Copris nevinsoni	0.29		1.31	28.26	nd	3.68		1.75				10.36	40.24	12.94			Rumpold and Schlüter (2013)
Helicopris bucephalus	0.91		40.34	13.25	1.61	40.63	2.13	0.65					nd				Rumpold and Schlüter (2013)
Holotrichia parallela	0.53	0.19	13.29	7.05	1.10	40.75	35.72			0.20	0.61				0.13	0.08	Yang *et al.*, 2014
Holotrichia spp.	nd		0.77	27.92	0.51	5.59		nd				13.86	47.26	nd			Rumpold and Schlüter (2013)
Onthophagus mouhoti	1.25		21.65	17.21	1.73	45.09	8.56	0.43					0.40				Rumpold and Schlüter (2013)
Onthophagus seniculus	1.66		23.86	17.82	2.95	43.00	7.54	1.38					0.60				Rumpold and Schlüter (2013)
Oryctes owariensis	2.50		0.20	0.23	37.60	5.24	45.46	4.19	1.22								Rumpold and Schlüter (2013)
Oryctes rhinoceros (larvae)	3.50		28.70	2.10	4.41	41.50	14.10	1.50					4.10				Rumpold and Schlüter (2013)
Palm Oil	1.23		41.78	3.39		41.90	11.03										Chowdhury *et al.* (2007)
Soyabean oil			14.04	4.07		23.27	52.18	5.63									Chowdhury *et al.* (2007)
Sunflower oil			6.52	1.98		45.39	46.02	0.12									Chowdhury *et al.* (2007)
Pork Lard			31.62	18.87		14.77	25.33	1.28									Sairin *et al.* (2016)
Beef Tallow			26.65	17.50		36.68	3.35	0.49									Sairin *et al.* (2016)
Chicken Fat			23.33	6.73		37.72	19.94	1.41									Sairin *et al.* (2016)

* nd = Not defined.

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TABLE 5 Mineral composition of some insect Scarabaeidae insect species

Mineral compostion [mg/100 g] based on dry matter / Species	Ca	K	Mg	P	Na	Fe	Zn	Mn	Cu	Se	Reference
Holotrichia parallela (Adult)	14.15	138.87	20.65	73.70		2.81	1.54	0.68	0.72		Yang *et al.* (2014)
Oryctes boas (larvae)	45.68		6.62	130.20		2.31					Rumpold and Schlüter (2013)
Oryctes boas (larvae)	6.11	19.55	7.12		38.54	1.47	2.12	0.39	0.11		Idowu *et al.* (2019)
Oryctes monoceros (larvae)	9.58	121.33	18.05		129.10	2.51	8.76	0.66	0.36		Idowu *et al.* (2019)
Oryctes owariensis (dried larvae)	46.39	72.78	266.47	76.94	88.68	15.85	4.87	5.67	0.76		Ukoroije and Bobmanuel (2019)
Oryctes owariensis (larvae)	48.57	84.37	270.91	93.86	47.57	18.68	6.95	5.92	0.85		Ukoroije and Bobmanuel (2019)
Oryctes rhinoceros (Adults)	35.48	49.62	58.73	84.85	37.67	5.87	3.68	1.08			Omotoso (2018)
Oryctes rhinoceros (larvae)	43.37	67.54	71.54	113.15	47.08	6.35	4.55	1.25			Omotoso (2018)
Oryctes rhinoceros (larvae)	0.04	0.20			26.28	4.94					Rumpold and Schlüter (2013)
Oryctes rhinoceros (pupae)	34.29	45.77	56.55	76.70	40.67	5.54	4.55	1.02			Omotoso (2018)
Phyllophaga sp. (Loc: Berwick-Canada)	0.06	1.28	0.19	0.69	0.16		166.13	19.83	21.87		Manning *et al.* (2023)
Phyllophaga sp. (Loc: Canning-Canada	0.05	1.30	0.19	0.71	0.17		170.66	31.00	22.66		Manning *et al.* (2023)
Phyllophaga sp. (Loc: Truro-Canada)	0.05	1.36	0.17	0.75	0.18		179.95	36.03	20.89		Manning *et al.* (2023)
Amaranthus caudatus (Amaranthus)			25.8		53.6	10.68	0.41		8.02		Rehman *et al.* (2014)
Abelmoshus esculentus (Okra)			23.62		11.5	10.68	0.28		7.42		Rehman *et al.* (2014)
Solanum melongena (Aubergine)			14.2		10.7	10.69	0.35		9.32		Rehman *et al.* (2014)
Raphanus sativus (Radishes)			17.0		72.6	11.64	0.87		8.85		Rehman *et al.* (2014)

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tial addiction (Rietjens *et al.*, 2017). Soluble oxalates bind calcium and magnesium as they pass through the digestive tract, rendering these minerals unavailable for absorption and utilization. Calcium is a mineral that the body need for good bone growth and maintenance. It also plays a role in various hormonal and enzymatic activities, as well as nerve impulse coordination. Soluble oxalates are expelled through the kidneys if absorbed, where they can promote the formation of stones (calcium oxalate crystals). Oxalates that are insoluble have no metabolic role in the body.

Various insect species, including *O. boas* and *O. monoceros* larvae, as studied by Idowu *et al.* (2019), exhibit differing levels of tannins, phytates, oxalates, and saponins. The larvae of *Oryctes owariensis*, examined by Ukoroije and Bobmanuel (2019), contain substantial tannins, phytates, and saponins, alongside alkaloids. Similarly, *O. rhinoceros* adults, larvae, and pupae, analyzed by Omotoso (2018), display varying quantities of tannins, phytates, oxalates, saponins, and alkaloids (Table 6). In contrast, legumes, grains, nuts, and tubers, outlined by Popova and Mihaylova (2019) showcase distinct ranges of tannins, phytates, oxalates, and saponins (Table 6). These diverse compositions underscore the intricate nutritional profiles of insects and plant-based foods, emphasizing the significance of their consumption within a balanced diet. While the presence of these compounds is acknowledged, their impact on human dietary utilization can vary based on factors like species, developmental stage, and preparation methods.

The presence and types of anti-nutritional compounds can vary among different species of scarabaeidae grubs. However, reducing anti-nutritional compounds in edible insects like can be challenging due to limited research specific to this insect group. Soaking scarabaeidae grubs in water before processing can help reduce some anti-nutritional factors. Traditional processing procedures involving aqueous systems, boiling, and heating have been shown to diminish antinutrient levels in foods, notably insects. Cooking properly is therefore recommended to lower oxalate concentrations in foods to allowable limits (Viol *et al.*, 2013), while still allowing consumers to benefit from the other phytochemicals included in insects. Discarding the soaking water can help remove leached compounds (Bukkens *et al.*, 2005). Proper drying of scarabaeidae grubs can help reduce moisture content and inhibit the growth of molds and fungi, which can produce anti-nutritional mycotoxins. However, the literature on the specific effects of drying on anti-nutritional compounds in scarabaeidae grubs is limited. Cooking or heat-processing scarabaeidae grubs can help reduce some anti-nutritional compounds. For example, a study on edible insects, including beetles, found that cooking significantly reduced the levels of anti-nutritional factors such as phytates and tannins (Mlcek *et al.*, 2014). Fermentation processes can also be applied to reduce anti-nutritional compounds. Fermentation by lactic acid bacteria, for example, has been shown to reduce phytate content in other edible insects (Yi *et al.*, 2013). However, further research into appropriate processing techniques is essential to maximize the nutritional benefits while minimizing the effects of these anti-nutritional factors.

6 Nutraceutical properties and medicinal uses of edible Scarabaeidae

Edible insects have been popular in traditional oriental medicine as a cure for gastritis, fever, cough, asthma, arthritis, rheumatism, and diabetes (Siddiqui *et al.*, 2023d; Mason *et al.*, 2018). Scientific research has concentrated on the positive characteristics of insects for human health due to their acknowledged pharmacological capabilities (Ratcliffe *et al.*, 2014). According to recent research, edible insects can provide bioactive compounds like phenolic compounds and flavonoids (Baiano, 2020) which act as antioxidants, anti-inflammatory, anticancer, antimicrobial, and antibacterial inhibitors of the pancreatic lipase enzyme, insulin regulators, and glycemic inhibitor (Martins *et al.*, 2022). Scarabaeidae are commonly consumed in rural and farming cultures and resulted in different nutritional and bioactive chemical compositions in insects, as well as considerable of beneficial bioactive compounds. Although positive benefits are frequently attributable to the synergy of multiple components, some studies suggest that polyphenolic content plays a critical role in certain bioactive activities. For example, in vitro investigations have shown that polyphenolic compounds obtained from extracts of house crickets (*Acheta domesticus*), mealworms (*Tenebrio molitor*) (Imathiu, 2020) and dark black chafer beetles (*Holotrichia parallela*) (van Huis, 2021) have antioxidant properties. An *in vivo* investigation in mice demonstrated that phenolic components in a vegetal tea and an insect tea (*Hydrillodes repugnalis*) have antioxidant properties (Belluco *et al.*, 2013).

Phenolic compounds are known to have a variety of bioactivities associated with chronic diseases, including antioxidant, anti-inflammatory, and anticancer prop-

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TABLE 6 Antinutrient composition of some Scarabaeidae insect species

Insect species	Taninin (mg/g)	Phytate (mg/g)	Oxalate (mg/g)	Saponin (mg/g)	Alkaloids (mg/g)	Reference
Oryctes boas (larvae)	0.04	0.01	0.54			Idowu *et al.* (2019)
Oryctes monoceros (larvae)	0.05	0.05	0.18			Idowu *et al.* (2019)
Oryctes owariensis larva (dried larvae)	5.39		1.28	1.49	2.35	Ukoroije and Bobmanuel (2019)
Oryctes owariensis (larvae)	5.78		1.56	1.72	2.43	Ukoroije and Bobmanuel (2019)
Oryctes rhinoceros (Adults)	4.22	41.07	1.19	2.59	3.35	Omotoso (2018)
Oryctes rhinoceros (larvae)	5.60	37.00	1.31	1.51	2.44	Omotoso (2018)
Oryctes rhinoceros (pupae)	6.75	39.43	1.33	3.05	4.99	Omotoso (2018)
Legumes	1.8-18	386-714	8.00	106-170		Popova and Mihaylova (2019)
Grains		50-74	35-270			Popova and Mihaylova (2019)
Nuts		150-9400	40-490			Popova and Mihaylova (2019)
Tubers	4.16-6.72	0.06-0.08	0.4-2.3			Popova and Mihaylova (2019)

erties. Furthermore, the antimicrobial bioactivity of phenolic compounds against several pathogenic and non-pathogenic microorganisms has been extensively studied as a result of the growing concern about microbial resistance to conventional antibiotic treatments and the interest in developing clean-label food preservatives that will eliminate the use of synthetic compounds in the food industry. Insect phenolics have yet only been tested for antioxidant bioactivity. However, protein and peptide fractions in insects such as tropical banded crickets (*Gryllodes sigillatus*), mealworms (*Tenebrio molitor*), and desert locusts (*Schistocerca gregaria*) are widely attributed to their overall bioactivity toward oxidation, inflammation, hypertension, and glucose inhibition. Currently, most insect phenolics have been tested for antioxidant bioactivity. Insect kaempferol and quercetin, on the other hand, can lead to various biological functions. Phenolic chemicals breakdown peroxide species and neutralize free radicals (Tao and Li, 2018), and they can attach to metal ions depending on the quantity and location of hydroxyl groups in the molecule (Elhassan *et al.*,2019).

A chemical molecule that inhibits or delays the oxidation of another compound is known as an antioxidant (Raheem *et al.*, 2019b). Because every oxidation reaction implies a reduction reaction, a substance capable of inhibiting oxidative processes is referred to as a reductant (da Silva Lucas *et al.*, 2020). However, because the latter pertains to biological processes, an antioxidant is not always an antioxidant. Antioxidants are classified as “primary antioxidants” when they actively inhibit oxidation reactions via the hydrogen-atom transfer mechanism or the single electron transfer mechanism, or as “secondary antioxidants” when they prevent oxidation via indirect reactions by chelating a metal atom that serves as an oxidation catalyst, or when they act as oxygen scavengers (Craft *et al.*, 2012). Phenolic compounds are considered primary antioxidants as they are able to neutralize free radicals and decompose peroxide species.

The integration of phenolic compounds in insects has been demonstrated by comparing the phenolic composition of the host plant to the ability of these compounds to sequester and metabolize dietary phenolics. This significant discovery has implications for edible insect farms that adopt a standardized diet. In addition to consuming phenolic chemicals, insects can synthesis phenolic compounds and incorporate them into their cuticles via the sclerotization process. Further research on insect phenols revealed interesting bioactivities. When the primary phenolic compounds found in insects, such as kaempferol and quercetin, are directly isolated from plants, they exhibit anti-inflammatory,

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antioxidant, anticancer, and antibacterial effects (Kim *et al*., 2022).

Insect phenolics have the potential to exert anti-inflammatory, anti-cancer, and antibacterial bioactivities. More research is needed to get fresh insights into the potential of insect phenolics and their impact on human health. The research on this topic appears promising, as the same chemicals found in insects, primarily quercetin, kaempferol, and catechin, have bioactivity when derived from plant sources. Several phenolic substances, primarily quercetin, kaempferol, (-)-epicatechin, and luteolin, have anti-inflammatory properties and have been shown to interfere at various stages of the pro-inflammatory pathway (Kim *et al*., 2022). Aside from anti-inflammatory bioactivity, anti-cancer activity appears promising since various studies have shown that phenolic compounds like kaempferol, quercetin, and myricetin can operate as anti-carcinogenic substances due to their antioxidant and prooxidant capabilities (Kim *et al*., 2022).

In one study, quercetin was found to have anti-cancer effect in prostate cancer cells through regulating tumor suppressor genes and downregulating oncogenes (Kouřimská and Adámková, 2016). In a separate cell study, myricetin was found to have significant anticancer activity in 1,2-dimethylhydrazine-induced carcinogenesis in colorectal cancer, demonstrating a decrease in tumor incidence in rats and an increase in antioxidant enzymes such as catalase and glutathione peroxidase (Williams *et al*., 2016). Finally, among all phenolic compounds, flavonoids (primarily flavones, flavonols, flavane-3-ols, and chalcones) exhibit the greatest antimicrobial activity via a variety of mechanisms attributed to their amphipathic properties, which are provided by hydrophobic substituents such as alkylamino chains and the presence of the heterocyclic ring (Kunatsa *et al*., 2020). Flavonols have been shown to be effective against gram-positive bacteria such Staphylococcus aureus and *Lactobacillus acidophilus*. Quercetin and myricetin have been shown to have superior antibacterial effects against *Staphylococcus aureus*, methicillin resistant, and *Staphylococcus* epidermis (Kunatsa *et al*., 2020). Given the antimicrobial bioactivity of plant phenolics and evidence that these phenolics are taken by insects, potential antibacterial capability in insect chemicals is a possibility. In many investigations, antibacterial bioactivity has primarily been linked to insect chitin and chitosan (Viol *et al*., 2013).

Extracting these nutraceutical and medicinal compounds from Scarabaeidae can be a complex process, and research specific to this insect group is relatively limited compared to other sources. However, some general methods can be adapted for extracting such compounds from scarabaeidae beetles. The solvent extraction method can be used for extracting various compounds, including phenolics and flavonoids (Barakat *et al*., 2016). Supercritical fluid extraction can be efficient for extracting compounds like lipids from insects, although it may require specialized equipment (Yang *et al*., 2015). Enzyme-assisted extraction can be effective for extracting proteins and other compounds from insect tissues (Chen *et al*., 2016). Ultrasound-assisted extraction can be employed to extract a range of compounds from insects, including proteins and phenolic compounds (Nongonierma and FitzGerald, 2017). Bioassay-guided fractionation can prioritize fractions containing target nutraceutical or medicinal compounds (Kim *et al*., 2017). The specific extraction process for scarabaeidae beetles may require optimization and validation due to potential variations in compound profiles among different beetle species. Additionally, it's important to ensure that the beetles used for extraction are sourced from safe and controlled environments, free from contaminants.

7 Safety concerns and consumer acceptance of edible Scarabaeidae as human food

When compared to the main nutrition, motives of price, taste, and quality that have commonly been observed in prior research (van Huis, 2016), the level of reported environmental incentive for consuming insects was considerable (33%). Indeed, surveys with UK consumers show that the proportion of participants who reportedly prioritize ethical or environmental factors when selecting specific food products is low (Shockley and Dossey, 2014). According to a market research poll in which individuals were asked to choose from a pre-defined list of factors, the percentage is 19 per cent. Another study, which did not provide participants with a choice of factors to pick from (like the current study), revealed that only 2% were influenced by environmental issues while purchasing food (Shockley and Dossey, 2014). As a result, the current findings suggest that those who are likely to try insect-based meals have a greater than average level of environmental concern, which is reflected in their dietary orientation and preferences. The most notable manifestation of this was in regard to meat intake. As previously stated, there were a disproportionately large number of meat-reducers among the

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participants. Based on this information, it appears that the intended market for insect-based convenience foods is people who are more 'flexitarian' than the ordinary person. However, as demonstrated below, the strong environmental motives for trying insects for the first time were insufficient to secure a repeat purchase.

According to Sogari (2015), a belief that insect products were beneficial to one's health also drove initial intake (24%). For meat eaters, this was generally because insects are lower in fat than conventional meat, whereas for vegetarians (who were still willing to eat insects) or those with mixed diets, it was generally because insects were perceived to be relatively high in protein and nutrients when compared to other meat alternatives, such as veggie burgers. The nutritional, environmental, and economic benefits of entomophagy are well documented in scholarly literature (e.g. as well as publications from international organizations such as the Food and Agriculture Organization of the United Nations) (Kipkoech *et al.*, 2023). However, it is unclear how much public understanding of the broader benefits of entomophagy might influence consumer acceptance of insects as food. It has been proposed that teaching consumers about the benefits of eating insects enhances their willingness to try them (Kipkoech *et al.*, 2023). Thus, consumer views toward the justifications for eating insects were investigated, as well as the elements that were likely to impact willingness to try insects.

The acceptance of edible scarabaeids is influenced by a complex interplay of nutritional value, cultural norms, regulations, education, culinary appeal, and economic factors (Supplementary Table S2). Nutritional value is one of the primary rationales for accepting edibles scarabaeids. Many scarabaeid species are rich in protein, essential amino acids, vitamins, and minerals, making them a valuable source of nutrition, especially in regions with prevalent protein deficiencies (Idowu *et al.*, 2019; Köhler *et al.*, 2019). Sustainability is another crucial factor as scarabaeids are often reared on organic waste materials like dung or decaying plant matter, effectively converting waste into protein, thus appealing to those concerned about food security and ecological impact (Holter, 2016). Cultural significance plays a role in acceptance, with scarabaeids considered traditional foods in some cultures, forming an integral part of local culinary practices (Chakravorty *et al.*, 2011). Preserving these traditions is a rationale for their acceptance. Furthermore, economic benefits are evident as communities involved in the collection, rearing, and sale of scarabaeids, especially women and teenagers, find a source of income (Anankware *et al.*, 2016; Ebenebe *et al.*, 2017; Mandirotya *et al.*, 2022; Ukoroije and Bobmanuel, 2019). Scarabaeids also present entrepreneurial opportunities in the emerging edible insect market. Aligning with environmental consciousness, the use of scarabaeids aligns with the desire to reduce the environmental footprint of food production. They require less land, water, and feed compared to traditional livestock, contributing to sustainable food production (Hodge, 2023). To promote their acceptance, addressing these factors and highlighting the potential benefits of incorporating scarabaeids into diets and food systems is essential.

Specific certifications or regulations for labeling edible Scarabaeidae products as human food may not exist. However, general food safety certifications and guidelines such as HACCP, ISO 22000, GMP, FSSC 22000, USDA Organic, Non-GMO Project Verified, Halal, Kosher, Allergen-Free, Third-Party Audited, and country-specific certifications can be applied to indetify the product of edible Scarabaeidae as human food. Organizations like the North American Edible Insects Coalition may provide entomophagy-specific guidance. For consumer safety, it is recommended to ensure that Scarabaeidae based food product complies with food safety regulations and standards in your region. For example, in the United States, the FDA oversees food safety (FDA- Food Safety Modernization Act) (FDA, 2023a). Following specific regulations related to the approval and labeling of novel Scarabaeidae foods (EU- Novel Foods Regulation) (EU, 2023) and allergen labelling (FDA- Food Allergen Labeling and Consumer Protection Act) are recommended (FDA, 2023b).

8 Rearing and harvesting of edible Scarabaeidae

Rearing chambers, which can range from small containers appropriate for a single pair of beetles to massive field cages, are an essential component of a rearing system (Siddiq *et al.*, 2013). The container size must correspond to the biology of the target insect as well as the anticipated scale of the rearing operation (e.g. single vs numerous breeding pairs per container). An appropriate container must meet the physical needs of the target insect (e.g. thermal conditions, gas exchange, and humidity management) and be non-toxic to both adults and developmental stages (Slagle and Davidowitz, 2022). The availability, pricing, storage, laboratory facilities, and cleaning requirements all influence container selection (Ebenebe *et al.*, 2017). Similarly, when

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rearing insects, one must pay close attention to nidification behavior when evaluating container dimensions and materials (for example, utilizing cardboard containers is a terrible idea because many dung beetles can dig through the container). The container dimensions, for example, would be determined by the tunneling depth and the size of the target buildings. For example, *Onthophagus vacca* reproduced successfully in containers containing medium to a depth of 20 cm. Similarly, telocoprid species (dung beetle that rolls a pile of dung) require large containers to allow adults to roll dung heaps; however, the depth can be less than that necessary for paracoprids (dung beetle that excavates below a pile of dung), which have deeper tunnels, which are now used for research purpose and recommending for consumption shown in Table 7.

The number of containers required is determined by the purpose and magnitude of the operation. Dung beetle rearing for an experiment, for example, could be accomplished in a single or a few rearing vessels. If many species or thousands of offspring are needed, different amounts and sizes of rearing vessels are likely to be necessary. A more feasible option in such a setting has been to deploy huge outdoor rearing facilities or multiple rearing cages (Alamu *et al.*, 2013), such as adapted bulk containers or raised garden beds designed to breed target dung beetles in semi-controlled environments. Scarabaeidae innovations produces hundreds of thousands of dung beetles of various species using over 600 1-cubic-meter plastic intermediate bulk containers (pallet tanks) (Thotagamuwa *et al.*, 2023). This allowed for the uniform upbringing of more larvae in a smaller, more controlled environment, as well as the observation and management of the developing offspring.

The harvesting of edible scarabaeids is primarily a household subsistence activity, although some edible insects are sold. Women and teenagers are the categories involved in edible insect collection (Meutchieye *et al.*, 2016). Harvesting methods for scarabaeid grubs can vary significantly. The choice of harvesting technique depends on factors such as the species of scarabaeid, the method of rearing, the local environment, and the intended use, whether for personal consumption or commercial purposes. It is essential to ensure sustainable harvesting practices that do not deplete scarabaeid populations or harm the ecosystem, and it's important to adhere to local regulations and guidelines when harvesting edible scarabaeids or any other insects for food.

Harvesters commonly employ four methods to collect scarabaeids, namely semi-domestication, handpicking, light trapping, and net trapping (Meutchieye *et al.*, 2016). Typically, handpicking and light trapping are used for harvesting grubs from their natural habitat (Ishara *et al.*, 2023). For instance, the grubs of certain beetle species are harvested directly from trees infested by adult beetles. This is achieved by cutting the infested trees and handpicking the grubs, as seen in the case of *O. monoceros*, which lays its eggs in the trees through natural openings or injuries, soil around young oil palms, adult oil palms, dead standing palms, and piles of empty fruit bunches (Ogbalu and Williams, 2015). Phototrophic species can be harvested using methods such as setting up light traps and nets, particularly for gregarious flying insects (Meutchieye *et al.*, 2016). Additionally, some beetle grubs are harvested regularly when the beetles are reared in controlled environment chambers, as is the case with some dung beetles (Thotagamuwa *et al.*, 2023). Nevertheless, it is essential to improve the practices and technologies used for harvesting these insects to meet international standards, thereby increasing market potential, and capitalizing on the economic benefits of edible insects (Ishara *et al.*, 2023).

9 Processing and packaging of edible Scarabaeidae as human food

Scarabaeidae's adoption of more palatable and nutrient-dense dung sources for dung beetle feeding has opened up a new market for diversification. Our understanding of how non-herbivorous insects diversify thanks to angiosperms' indirect influence is expanded. The discovery that scarabaeines evolved in the mid-Cretaceous and rapidly diverged before a source of suitable mammalian dung was available offers the first evidence that any insect group originated as a result of novel ecological interactions with dinosaurs and radiation due to specialization on a dinosaur resource, specifically their dung. The history of the Scarabaeidae has been rebuilt, and it demonstrates the intricacy of ecological adaption and evolutionary diversification as well as providing evidence for an extinction event that is not documented in the fossil record (Gunter *et al.*, 2016).

Processing of scarabaeidae beetles for human consumption involves several critical points that must be carefully considered to ensure food safety, quality, and compliance with regulations. First, sourcing and farming practices should ensure that scarab beetles come from safe and controlled environments with minimized contamination risks (van Huis, 2013). Proper harvesting techniques, particularly at specific life stages like larvae,

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TABLE 7 Studies that have explored the rearing requirements for Scarabaeidae species

Species	Temp. (°C)	Humidity (%)	Medium moisture (%)	Reference
Agrilinus ater, *Copris acutidens*, and *Copris hispanus*	14-18	–	24	Slagle and Davidowitz (2022)
Gromphas lacordairei	16-24	–	–	Davidowitz (2021)
Digitonthophagus gazella and *Onthophagus atripennis*	23-29	69-75	–	Ortiz *et al.* (2016)
Kheper nigroaeneus	15-20	–	–	Ortiz *et al.* (2016)
Bubas bison	20-25	–	–	Ortiz *et al.* (2016)
Allogymnopleurus thalassinus	15-20	–	–	Van Huis and Arnold (2013)

are crucial to prevent stress or damage (Ramos-Elorduy and Pino, 2006). Maintaining strict hygiene and sanitation standards throughout the processing facility is essential to prevent cross-contamination (Klunder *et al.*, 2012). Selecting appropriate processing methods such as blanching, roasting, frying, or freeze-drying, depending on the desired final product, impacts flavor, texture, nutrient content and energy availability (Halloran *et al.*, 2017) and also avoid ill effects on human health such as gut inflammation, risk of infections (Figure 10). Managing potential allergenic cross-contamination when processing scarab beetles alongside other ingredients is also important (Rumpold and Schlüter, 2013). Implementing quality control measures, including sensory evaluation, microbiological testing, and compliance with labeling regulations, ensures the product meets safety and quality standards (Megido *et al.*, 2018). Proper packaging and storage are vital for maintaining product freshness and preventing contamination, which extends shelf life (Kim *et al.*, 2021). Producers must adhere to regulatory compliance requirements and consider educating consumers about the nutritional value, sustainability, and safety of scarab beetle-based products to build acceptance and trust (Meneguz *et al.*, 2018; Sogari *et al.*, 2019). By focusing on these critical points, producers can ensure the safety and quality of scarab beetle products intended for human consumption.

Crush insects into powder or employ insect-derived products like protein, lipids, and chitin to reap the nutritional and sustainability benefits of consuming insects. Incorporating insects in a non-recognizable form (i.e. powder) may ease unfavorable views by allowing people to link bug powder-containing dishes with more familiar, staple items. According to studies, the low acceptability of edible insects is related to emotional factors (e.g. disgust) as well as unfamiliar tastes and textures, implying that incorporating insects as part of an ingredient could be a potential gateway for wider acceptance by Western consumers (Slagle and Davidowitz, 2022). For example, European and American consumers have expressed an interest in food products including insects.

Insect flours are normally made by dehydrating or roasting whole insects and then grinding them into a fine powder known as flour. However, due to chitin-protein interactions, the techno-functional properties (emulsification, foaming, solubility, etc.) of the protein present in these flours can be changed, limiting their use to make food products (Varelas and Vassileios, 2019). Enzymatic proteolysis of a protein's peptide bonds, heat treatments, solvent extractions, or alkali/acidic reactions that yield peptides with variable sizes and free amino acids are methods for generating insect protein powders that will allow for chitin separation. The alteration of the protein affects its activity by decreasing its molecular weight and adding polar groups, among other molecular configuration modifications (Van Huis and Arnold, 2013). Figure 11 depicts the process of extracting insect protein with commercial enzymes. Longer proteolysis times and higher enzyme concentrations result in lower molecular-weight peptides with various degrees of techno-functional features in this process. Similarly, the protease specificity chosen will alter the peptide amino acid sequence and/or amino acid residues, resulting in distinct nutritional and techno-functional features in protein hydrolysates (Hanboonsong *et al.*, 2013).

The highlight the primary technologies that can be utilized for processing insects, in addition to lipid and protein extraction methods; these are common processes widely employed in the industry for various food and feed commodities. For example, blanching (using boiling water or steam) is largely used to inactivate endogenous enzymes found in food, or in this case, insects, which might deteriorate or destroy the product (Hanboonsong *et al.*, 2013). Blanching can also reduce

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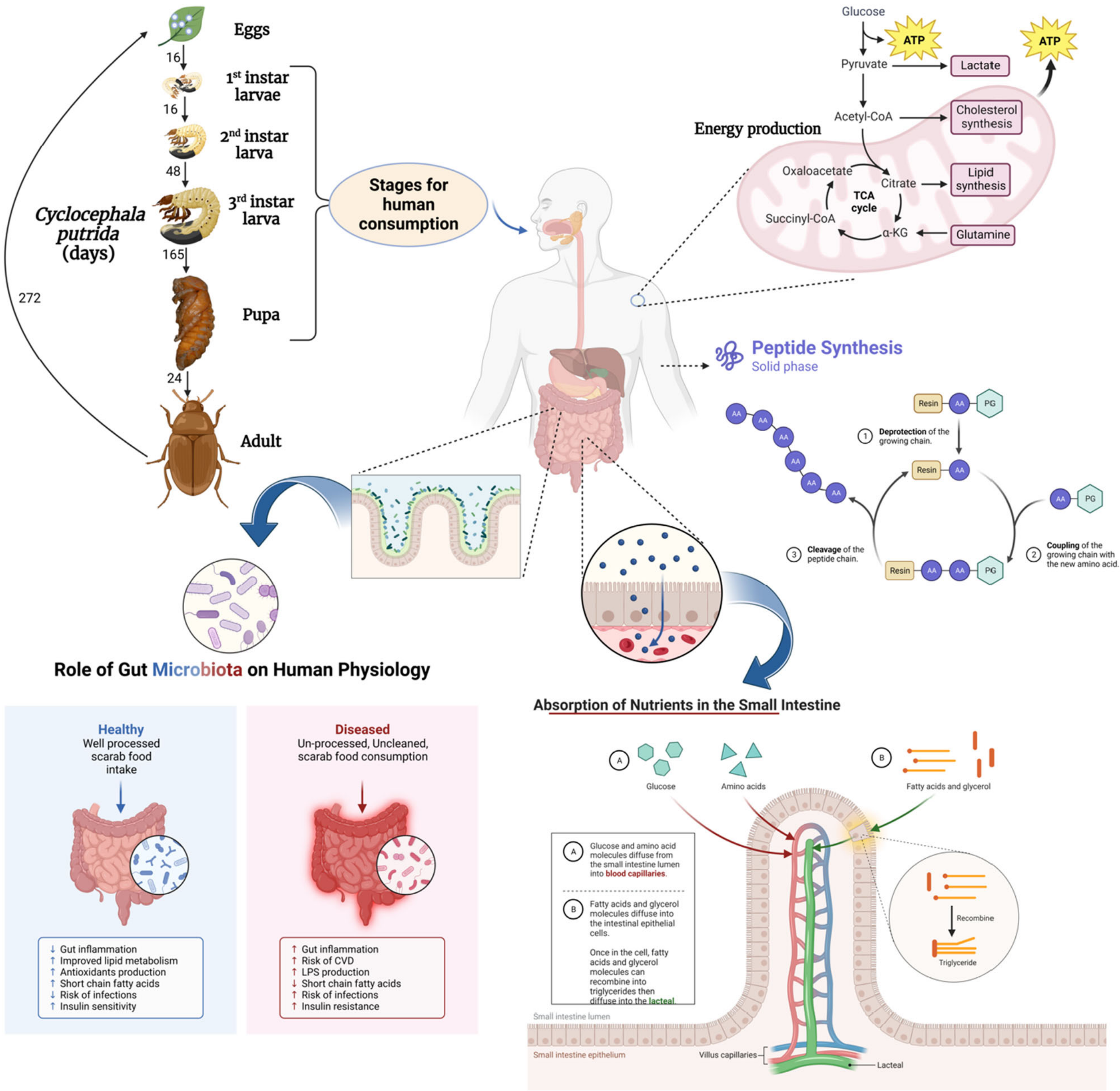

FIGURE 10 Schematic overview on human consumption and bioenergy synthesis profile of *Cyclocephala putrida*.

early microbial loads, notably those of mesophilic bacteria (Dossey *et al.*, 2016). Others have also used pasteurization (at temperatures lower than 100°C) to inactivate enzymes and eliminate harmful germs (Dossey *et al.*, 2016).

For edible insects, low-temperature techniques such as refrigeration and freezing have also been documented in the literature. These procedures have the advantage of not considerably altering the visual or sensory properties of the meal (Seiyaboh and Izah, 2020). Freezing the water in the food at temperatures below 18 °C reduces aw, extending the food's shelf life by months or years, depending on the product. De Smet *et al.* (2019) found that spoilage-causing bacteria continued to grow on mealworm paste held at 4 °C, reaching a food spoiling level after two weeks, whereas mealworm paste stored at 21 °C did not increase the microbial load for up to three months (Siddiq *et al.*, 2013).

Because of its appealing sensory features and improved nutritional quality, fermentation technology has lately been advocated as a viable approach in the creation of insect-based meals. Castro-López *et al.*(2020) present a comprehensive review of the current research on fermented edible insects, as well as additional applications of fermentation technology on insects (Siddiq *et al.*, 2013). Fermented insect sauces, in this context, have been shown to have acceptable sensory qualities and to be a promising alternative for the

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development of umami-style sauces such as soy sauce. In contrast, Veralas and Langton suggest that, because of their complex microbiota, insects can be utilized as 'starters' for the manufacture of artificial diets, among other things (Varelas and Vassileios, 2019).

Packaging scarabaeidae is an important component of the food supply chain. Packaging makes easier for transportation (Smetana *et al.*, 2016; Varelas and Vassileios, 2019; Varelas, Vassileios Langton; Maud, 2017). In edible scarabaeidae, conventional packaging materials such as plastic, paper, glass, metal, and composites have limits. Plastics such as polyethylene, polypropylene, and polyethylene terephthalate are harmful to the environment (Smetana *et al.*, 2016), ending up in health issues (Aguilera *et al.*, 2021).

Consumers' changing attitudes regarding scarabaeidae packaging, quality, disposal behaviors, and environmental concerns are prompting researchers and manufacturers to use bio-based sustainable packaging materials and circular economic processes in the modern day. Edible scarabaeidae packaging has the potential to be a future, environmentally friendly packaging solution. Consumers can ingest edible packaging materials as long as they are generated from natural food-grade polymers such as polysaccharides, proteins, or lipids (Siddiq *et al.*, 2013). Edible scarabaeidae packaging preserves quality, improves shelf life, and, to some extent, reduces waste. Edible scarabaeidae materials can now be turned into edible films and coatings thanks to technological breakthroughs and the availability of cutting-edge converting methods. The addition of antimicrobial agents and antioxidants to packing scarabaeidae materials may slow the ripening process and extend shelf life (Aguilera *et al.*, 2021).

The mixing of more than one edible packaging material to improve overall packing qualities is known as composite packaging. Although polysaccharides and protein-based films have high gas barrier characteristics, they lack water vapor barriers. As a result, composite films are created by mixing lipid components into a polysaccharide or protein-based polymer matrix. The bilayer approach can also be used to create a composite film in which one layer is lipid-based and the other is hydrocolloid-based. The bilayer coating method involves coating dried hydrocolloid film with lipid content. Some lipids and hydrocolloids are present in the film. The lipid phase will separate from the polysaccharide or protein phase during the drying process. This technique also results in the formation of a bilayer with better characteristics (Aguilera *et al.*, 2021).

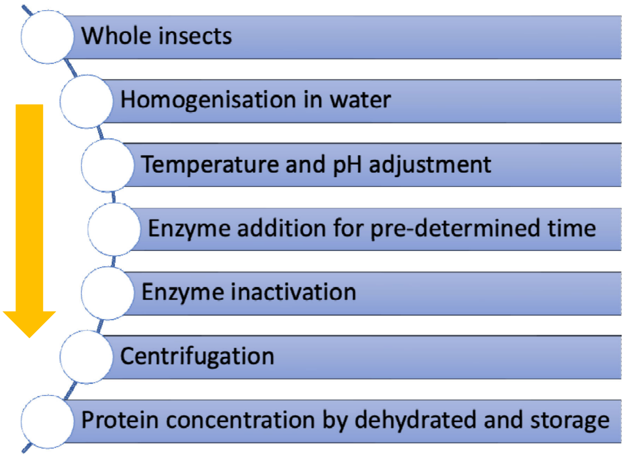

FIGURE 11 Flowchart diagram for production of protein hydrolysate powders using whole insects as starting material.

10 Future perspectives and conclusions

Scarabaeidae as a human food source is promising within the broader context of entomophagy. As the global population continues to grow and concerns about sustainable protein sources and environmental impact intensify, edible insects are gaining attention. While scarabaeids, such as certain dung beetles or rhinoceros beetles, are not currently a mainstream food source, they possess potential.

Scarabaeids are known for their significant nutritional value, being rich in protein, minerals, fatty acids, antioxidants, and various bioactive compounds. These components are essential for human nutrition and contribute to their remarkable nutraceutical properties. Edible scarabaeidas are rich natural sources of numerous phytochemicals that can be used in the food, pharmaceutical, medicinal, and cosmetic industries. Therefore, more research on these insects is advised for possible product development in the food, pharmaceutical, medicinal, and cosmetic industries. It is also suggested that cyanogenic glycosides in insects should be quantified in order to extrapolate their safety for human intake. Furthermore, future research into probable antioxidant activity from the phytochemical content studies on these neglected insects may be considered. The anti-nutrients of the beetles can be efficiently reduced by boiling and heating to levels that are not toxic to consumers. However, asuggestion for future research is also offered for certain processing procedures and settings that may reduce anti-nutrient levels to acceptable concentrations for all of the insects evaluated in the study.

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The potential bioactive qualities of insect phenols suggest that entomophagy may provide additional health benefits to the human diet in addition to nutritional value. The integration of phenolic compounds in insects has been demonstrated by comparing the phenolic composition of the host plant to the ability of these compounds to sequester and metabolize dietary phenolics. This significant discovery has implications for edible insect farms that adopt a standardized diet. In addition to discovering phenolics, insects can synthesize them and incorporate them into their cuticle via the sclerotisation process. More research is needed to determine the contribution of these cuticle phenolics to the overall phenolic content of insects. More research on insect phenols could lead to the discovery of new bioactivities and recommends that eating insects should be done in moderation.

Future research and development efforts may also focus on species selection, optimizing rearing practices, and addressing cultural acceptance and regulatory challenges. With proper scientific investigation, improved processing methods, and effective marketing, scarabaeidae could become a valuable and eco-friendly protein source, particularly in regions facing food security and environmental sustainability issues. However, the extent to which scarabaeidae can fulfill this role will depend on continued exploration and investment in the field of entomophagy. Continued research into edible beetle species, their taste profiles, and culinary applications could lead to the development of new food products and dishes that incorporate Scarabaeidae.

Supplementary material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.24421354

Author contributions

Shahida Anusha Siddiqui: Conceptualization, methodology, validation, data curation. Writing: original draft, review and editing, visualization, supervision, formal analysis, project administration, investigation, resources. Kwame Attafuah Ampofo: Writing: original draft. Eric Kuuna Dery: Writing: original draft. Akpe Mary Eddy-Doh: Conceptualization. Roberto Castro-Muñoz: Validation, funding. M. Pushpalatha: Review and editing. Ito Fernando: Writing: Review and editing.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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