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REVIEW ARTICLE

Edible beetles (Coleoptera) as human food – A comprehensive review

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Abstract

The consumption of edible Coleoptera, or beetles, is examined in this review as a viable remedy for the rising world food demand brought on by the population's predicted expansion to over 9 billion by 2050. The review illustrates the nutritional profile of beetles, highlighting their high protein content, good fats, and oils, while being low in saturated fats and high in omega-3. Beetles have a rich history of consumption, with over 2 billion people, particularly in regions like Africa, Asia, and the Americas, incorporating them into their diets. They contribute significantly to human nutrition while also playing essential ecological roles, including soil fertilization and pollination. Beetles represent a promising solution to combat climate change, as traditional livestock production is a major greenhouse gas emitter, and beetle farming boasts lower emissions, reduced resource requirements, shorter life cycles, and superior feed conversion rates. Notwithstanding their advantages in terms of nutrition and the environment, there are obstacles including customer adoption, safety worries, and legal limitations. The review also covers how beetles are processed into different food items, such as liquids, pastes, and powders, and how these products are used in the feed, food, and nutraceutical industries. In general, edible beetles present a viable substitute food source with noteworthy nutritional and ecological benefits; yet, additional investigation and endeavors are required to surmount obstacles to their extensive integration.

Keywords

Coleoptera – beetle consumption – nutritional value – safety concerns – culinary uses – sustainable protein source

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1 Introduction

Especially in parts of the world where insects are estimated to be present in the diet of around 2 billion people (Africa, Asia, and America) (Raheem *et al.*, 2019a). Approximately 31% of the edible insect species consumed in the world are Coleoptera species, namely beetles (Papastavropoulou *et al.*, 2023). In addition to human nutrition, insects also play a role in maintaining ecological balance such as fertilization of soil through the recycling of biological wastes, carrying pollen for plant propagation, etc. (van Huis *et al.*, 2013). They offer a potential answer to the urgent issue of climate change, as conventional livestock production is a significant contributor to greenhouse gas (GHG) emissions. To mitigate this, edible insect farming is characterized by lower GHG impacts, reduced area and water use, shorter lifespans, and higher feed convertibility rates compared to conventional livestock (Park *et al.*, 2022). In addition, throughout history, humans have consumed edible insects for both nourishment and medicinal purposes or to produce honey and silk to produce products which are useful for humans. Nowadays, these insects are gaining recognition as a promising alternative food source, offering both nutritional and therapeutic advantages. The insect food industry is rapidly progressing, introducing innovative products like powders, liquids, and oils for various uses (Dossey *et al.*, 2016a; van Huis *et al.*, 2021a). Insects also hold the promise of serving as a viable replacement for traditional sources of animal protein, such as cattle, pork, and poultry, and may become a fundamental element of tomorrow's food products (Rovai *et al.*, 2021; Krongdang *et al.*, 2023). Insects are becoming a more popular source of protein, and the industry is expected to expand to US $8 billion over the next ten years. Insects can be processed to provide flours, powders, and protein hydrolysates. Harvesting, initial processing, decontamination, further processing, packing, and storage are all steps in the processing process. For disinfection, a variety of methods are employed, including toasting, drying, blanching, frying, marinating, and smoking. Additionally, novel methods like ultrasonic therapy and cold plasma are being investigated. The procedure seeks to satisfy customer needs, maintain quality standards, and guarantee food safety. Optimal storage settings are recommended to preserve microbiological quality, and these parameters vary based on the kind of beetle and product shape (Adámková *et al.*, 2017, Melgar-Lalanne *et al.*, 2019; Liceaga, 2022). Depending on the species, regional customs, and season, there are several methods for gathering and raising edible coleoptera. Using emergence or elector traps, window traps, and trunk window traps are a few popular techniques for collecting beetles. In addition, beetles can be physically gathered by entomological filtration, from their hiding places or the soil's surface, or at night from an artificial light source. The unique requirements of the species, such as the kind of food they consume and the temperature they require to thrive, must be considered during raising (Gobbi *et al.*, 2018).

Apart from their efficient production, insects are highly nutritious, and renowned for their rich protein content. They also contain significant levels of healthy fats and oils while being low in unhealthy components, specifically low in saturated fat and high in omega-3. Furthermore, insects offer a range of valuable nutrients, the exact composition varying by species and, in some instances, their diet. Insect-derived food ingredients, including powders, meals, pastes and liquids, have diverse use in the food, feed and nutraceutical sectors. These ingredients are incorporated into fortified dry products, protein supplements, high-protein cereals, meat alternatives, chitosan (a chitin-derived nutraceutical), protein-rich beverages, athlete supplements, and various snacks. like energy bars, burgers, or compound feed. In many tropical countries, insects are traditionally prepared by roasting, frying, or boiling them as a whole. Alternatively, they can be dried, ground, and incorporated into various food products (Pippinato *et al.*, 2020; Daub and Gerhard, 2022; Mancini *et al.*, 2022).

Insects are recognized as a valuable, nutritious, and sustainable food source, with a growing number of stakeholders, including consumers, businesses, startups, educational institutions, governments, and others, actively participating in the emerging insect-based food industry. Media coverage of this expanding sector has also significantly increased in recent years (Dossey *et al.*, 2016a). There are more than 2,000 species of edible insects in use around the world. The Coleoptera are the most commonly eaten group with 31.2% of total. Food quality index shows that Coleoptera are a well-balanced food source. Coleoptera can therefore be widely used in the food industry. They can be used as a dietary supplement, especially in the case of a vegetable diet on the basis of cereal proteins that are poor in essential amino acids. They can also be used in high protein food products (Orkusz, 2021). In view of these and many other reasons (detailed explained below), Coleoptera should be well marketed as a valuable natural resource that can be used both directly and/or indirectly in food products

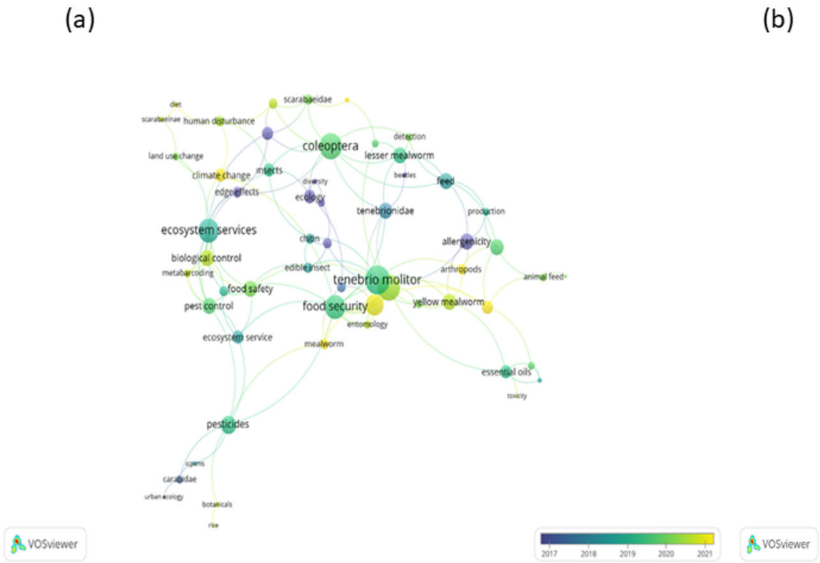

FIGURE 1 Bibliometric (a) overlay visualization of the researches on Coleoptera as a human food, showing a time period of the occurrence of the keyword from 2017 (blue) to 2023 (yellow), (b) network map of the research on Coleoptera as food for human beings shows the degree of relatedness of the scientific journals. This illustration was generated using VOSviewer (Jan van Eck and Waltman, 2023).

by exploiting their rich nutritional content and should be made widely available to mankind.

With nearly 9 billion people anticipated to live on the planet by 2050, food production must grow by 100%. However, because of things like global warming, there is less land available for agriculture, which might make food insecurity worse, especially in low-income countries. Rich in protein, vitamins, and minerals, edible insects are considered a great dietary source to combat food instability and malnutrition. Creating industries that produce insects might aid in enhancing socioeconomic circumstances and global food access. Insects may be widely used as food, but obstacles including consumer acceptability, safety worries, and regulatory restrictions still stand in the way (Rothman *et al.*, 2014; Belluco *et al.*, 2015; Moruzzo *et al.*, 2021).

In addition, overlay and network visualization diagrams were prepared based on the terms “Coleoptera”, “human” and “food”. The data was extracted from databases of Web of Science Core Collection and Scopus between the years of 2013-2023. In Figure 1a,b, the largest circular areas represent the most widely chosen terms by the authors. Based on this bibliometric mapping, it was possible to classify the terms into four different sets represented by four different colors. The different colors represent the clusters formed by the keywords. The minimum number of keyword occurrences is set to 9. 57 keywords met the limit. The relevancy rating was calculated for 57 keywords. Thus, 57 keywords were chosen to illustrate the connection between source titles and keywords.

This comprehensive review explores the consumption of edible Coleoptera (beetles) as a source of human food. It covers a wide range of topics, including records of beetle consumption, nutritional value (macronutrients and micronutrients) and nutraceutical properties. The review also discusses safety concerns, consumer acceptance, culinary uses, and preparation methods for edible beetles. It explores the environmental benefits of beetle consumption and examines cultural attitudes toward beetles as food in different regions. Additionally, the review delves into the harvesting, rearing, processing, and packaging of edible beetles and considers their potential as a sustainable protein source. It concludes by discussing future prospects, research areas, market potential, and offering overall perspectives on this topic.

2 Records of consumption of edible Coleoptera

According to the edible insects list of the world, there are more than 700 species belong to Coleoptera order (Jongema, 2017). In Supplementary Table S1, all edible Coleoptera species with their common names, consumption stages (larva, pupa or adult) and countries are given. For consumers, the biggest factor in incorporating edible insects into their diets is that they taste, smell and, if possible, look very similar to conventional foods (Kim *et al.*, 2019). Although there are many people in the world who consume insects unprocessed, for the majority the appearance of insects prevents them from being included in their daily diet (Kim *et al.*, 2022). Today, many companies produce snack bars, insect-based flour, granules and pastes that include edible insects (Gmuer *et al.*, 2016). Also, some upscale restaurants are trying to familiarize the public with edible insects by including them in their menus. There are restaurants in Denmark, Sweden, Finland and the United Kingdom that combine insects with gastronomy (Jansson *et al.*, 2019). In the last couple of years, insect cooking books, television shows, food fairs, and trade shows have attempted to regularize entomophagy, in contrast to earlier strategies that were based on advertising the novelty of products (Shelomi, 2015).

Steaming, roasting, smoking, frying, stewing, and curing are some of the traditional cooking techniques for edible insects (Hong *et al.*, 2018; Melgar-Lalanne *et al.*, 2019; Ojha *et al.*, 2021a). Blanching to reduce the number of food-borne microorganisms and to inactivate enzymes is used prior to these cooking techniques (Marshall *et al.*, 2016). For example, African palm weevil (*Rhynchophorus phoenicis Fabricius*, 1801)'s larva is roasted in a pan after cleansing and perforating with a sharp knife. Condiments such as tomato, chili, onions are added and after simmering of all ingredients, it is served with rice or pasta which is generally made from corn flour (van Huis, 2003). Edible insects are often promoted as snacks and can be coated with chocolate such as nuts, mixed into baked goods or sprinkled on salads. Weevils of *Polyclaeis equestris Boheman* and *Polyclaeis plumbeus Guérin* can be consumed after barbecued, roasted or boiled (van Huis, 2003). Moreover, larva of rhinoceros beetles (*Oryctes sp.*) is parboiled, then fried and served as a meat dish with tomato or other kind of sauce (DeFoliart, 2002). Whether lightly processed, fried, roasted, or fine-ground, they are used to add a unique flavor to foods or to enhance the nutritional profile of foods. Larva of *Caryobruchus* sp. (palm seed bruchid) is used as an ingredient of the bean flour (Costa Neto and Ramos-Elorduy, 2006). Additionally, in Thailand at least 194 species of edible insects are found (Durst and Hanboonsong, 2015; Köhler *et al.*, 2019; Krongdang *et al.*, 2023). The cooking method varies according to the type of insect such as fried locusts, roasted beetles and crickets. Insects can also be added to salads and chili paste (Krongdang *et al.*, 2023). Food raw material manufacturers produce ingredients such as insect flours. This enables their business partners to produce pasta, ramen noodles, bakery products or protein powder additives for both the global and domestic markets (Raheem *et al.*, 2019a; Krongdang *et al.*, 2023).

Tenebrio molitor (*T. molitor*) belonging to the Coleoptera:Tenebrioidae family, which has been extensively studied in academia and is commercially produced as bird, reptile and fish feed because it is easy to produce its larva, is a pest especially of stored grain. They usually feed and develop in grains such as wheat flour, corn flour, cake mixtures, cereals, meat residues, and chicken coop residues, which are ground or about to rot in damp and poor conditions (Riaz *et al.*, 2023). Commercially produced and widely consumed in Asian and European countries, mealworms are rich in protein, fat and minerals such as calcium and phosphorus. It contains all amino acids, especially as a protein source (Anusha and Negi, 2023a). *T. molitor* larva is currently used in the production of protein extracts, oils and flour. Regulation 2015/2283 of the European Union allows the use of this protein source as an innovative food in the production of pasta, biscuits and snack bars (EFSA Scientific Committee, 2015; Turck *et al.*, 2021; Errico *et al.*, 2022). In the study of Djouadi *et al.* (2022), from 2 to 20% (w/w) of *T. molitor* flour was added to formulation to produce protein-rich healthy crackers. In terms of sensory properties, panelists liked the crackers with 6% insect meal added. Although there was a decrease in firmness values as the amount of insect meal increased, the crispness value increased due to the increase in the amount of protein. In addition, the brightness values of the crackers decreased depending on the amount of insect flour. In another study, wheat flour and mealworm flour were replaced at different rates in the shortcake biscuit formulations. While an increase was observed in the amount of protein and ash contents with the increase in the amount of mealworm flour, no significant change was observed in the fat and energy values. It was determined that there was an increase in the free radical scavenging activity and the amount of slowly digested starch compared to the control product (Zielińska and Pankiewicz, 2020). Three different kinds of insects' flour (*Hermetica illucens*, *Acheta domestica* and *T. molitor*) were substituted at 5% of wheat flour in bread doughs in the study of González *et al.* (2019). Rheological properties such as water absorption and stability were negatively affected by the addition of insect flour. Moreover, the nutritional value of breads was increased by the incorporation of insects' flour. In another study, palm weevil larvae meal and orange-fleshed sweet potato flour were mixed in three different ratios (0, 35 and 70%) and used in biscuit production. It has the highest value in terms of energy value and fat content of biscuits

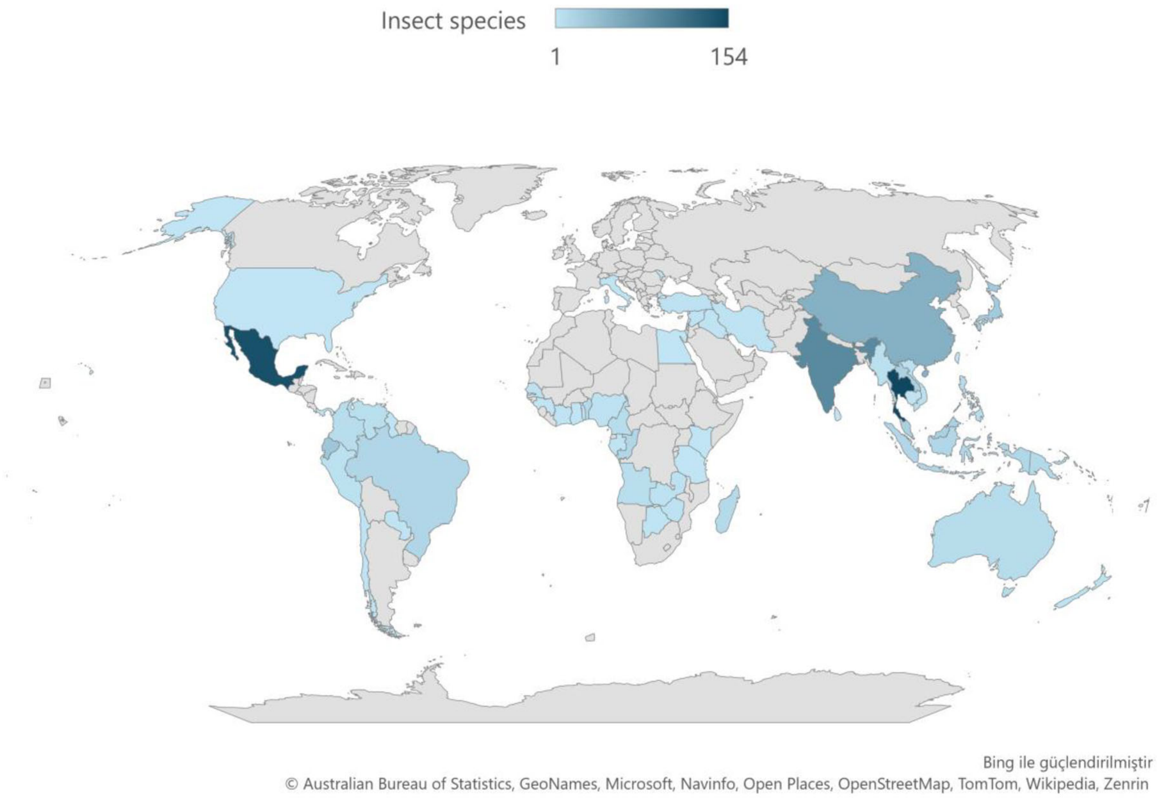

FIGURE 2 Number indication of edible Coleoptera species through Heat-map. The blueness depth responses to the number of edible Coleoptera species in each country.

containing 70% of larva flour. In addition, the amount of palm weevil larvae flour and the amount of calcium, iron and zinc increased in direct proportion. Also, the overall acceptability of biscuits was found to be high by pregnant women in Ghana (Ayensu *et al.*, 2019).

Insects have had a long relationship with humankind, serving as a source of cultural, religious, and economic insight. However, their value as a nutrition source has been crucial to human history, as humans have consumed insects continuously since pre-agricultural times (Jansson *et al.*, 2019). At least two billion people are thought to include edible insects in their diets, and there are currently more than 2,100 insect species recognized as edible worldwide. Beetles are among the most widely consumed insects in the world (Jongema, 2017). In Figure 2, edible Coleoptera species are illustrated in world heat map. The increasing blueness is in relation with the high quantity of species. According to Jongema's list (2017) of the edible insects in the world, the most species are found in Thailand, Mexico, India, China, and Ecuador, respectively.

3 Bioecology of Coleoptera

It has been recorded that Coleoptera reached its diversity approximately 155-160 million years ago. Due to the multitude of insect species, identifying a new species is complicated. There has been a dramatic growth of interest in the biology, ecology, and diversity of this group because of several reasons: (1) their importance in altering the land-based environment of an ecosystem; (2) Growing recognition of their economic importance; (3) their important role in forest disturbance, forest biodiversity and organic material degradation; and (4) Their important function in the different food chains, as their larva and hatchlings are a part of the diet of some insect-eating birds (Kritika and Jaimala, 2017). One of the most studied edible Coleoptera is *T. Molitor L.*, a yellow worm larva, which is about 2.5-3.5 cm long and weighs 0.2 g. It is known as a pest of uncontrolled stored grain products and is harvested and consumed in Africa, Australia, and Asia. According to the information reported in the literature, 50% of the grains are lost when infested by worms (Table 1) (Alves *et al.*, 2016; Feng, 2018). The species lays eggs between 4-17 days after mating. A female worm can produce about 500 eggs. Embryonic development of eggs can be increased if the temperature is increased

TABLE 1 Ecology of most consumed Coleoptera species

Beetle name	Name of beetle	Ecology	References
Mealworms	*Tenebrio molitor*	Grain products	Alves *et al.*, 2016
Scarab beetle	*Scarabaeidae*	Flower, tree sap, rotten wood, manure and carrion	Ghosh and Bhunia, 2016; Zorhansanga, 2021
Longhorned beetles, longicorns, capricorns, round-headed borers, timber beetles, goat beetles, or sawyer beetles	*Cerambycidae*	Shoots, Twigs, stems and roots of woody plants	Kariyanna *et al.*, 2017
Water beetle	*Belostomatidae*	Ponds, lakes, billabongs, Dams, and pools at the edges of the streams	Ghosh, 2011
Red flour beetle	*Tribolium castaneum*	Stored products: wheat, wheat flour, Cereal based foodstuffs such as biscuit, nuts, Beans, pasta, cornflakes, and even dried fruits	Abdullahi *et al.*, 2019
Ground beetles	*Caraboidea*	Biocenoses, Both forest and steppe; agro Landscapes	Jung *et al.*, 2013; Alekseev and Ruchin, 2020
Rove beetles	*Staphylinidae*	Nature, humid terrestrial environments	Work *et al.*, 2013
Coffee-bean weevil	*Araecerus fasciculatus*	Pest of warehoused products including coffee and cocoa beans	Bouchard *et al.*, 2017
Wood-borer beetle	*Xylophagous*	Woody tissues	Ruzzier *et al.*, 2023
Jewel beetle	*Buprestidae*	Leaves and stems, in the roots of herbs, soil dwellers	Al-Jahdhami, 2021
Pine sawyer beetle	*Monochamus scutellatus*	Pine trees	Naves *et al.*, 2008; Pajares *et al.*, 2010
Stag beetles	*Lucanidae*	Decaying wood	Huang, 2018
Passalids	*Passalidae*	Decomposed wood	Ulyshen, 2018
Scolytine and bark beetles	*Scolytinae*	Phloem of dead or dying trees	Bouchard *et al.*, 2017

between 25-27 °C. However, this period lasts usually between 4-6 days (Alves *et al.*, 2016). Then the larva is formed, and the larval period lasts about 3 months. During this period, insects can be collected and processed. Larva that are not collected enter the pupal stage and this period until adulthood lasts 5-6 days (Feng, 2018).

Furthermore, Scarab beetles can be small or large in size. The shape of the antennas makes them easy to identify. The scarab family is harmful to agriculture, forestry and some fruit trees, but feeds on manure and carrion. The properties benefit by reducing parasitic worms and flies in fertilizers (Zorhansanga, 2021). Scarab beetles are an indicator of whether the surrounding ecosystem has changed. The larval form of insects feed on plant roots and rotten wood. Adults feed on flowers, fruits, leaves and tree sap (Ghosh and Bhunia, 2016). Dung beetles make up about 70 percent of the insect population in Africa. They settle in tunnels up to 1 m deep under dung piles. They use the dung as a feeding and breeding medium. They use dung fluids, or dung, to feed the larvae. Larvae remain in the soil for weeks or months before emerging as adults (Brown *et al.*, 2010).

On the other hand, Cerambycids vary in size from 2.5 mm to 17 cm. It can be in different colors, sizes and decorations. Some longhorn breeds have been reported to range in length from 3.5 mm to about 12 cm. They are named longhorn because of the long antennae found in the males. While the adults feed by taking nectar or pollen from the flowers, the larvae and pupae feed on the bark of the trees. They mate on flowers or other host plants. Mating ranges from a few seconds to several hours. A female can produce 25-100 eggs in her lifetime. Larvae hatch in 1-3 weeks. The larval period can vary between 1 and 3 years. Larvae usually live in a tunnel they create behind wood dust. Pupal periods range from 1 week to 1 month. According to the breed, the seasons for adults to exit out are different (Kariyanna *et al.*, 2017). Rove beetles are insects found in humid terrestrial environments and are common in nature. It is also important in controlling arthropods such as some plant pests (Work *et al.*, 2013). Adult females lay about 8 eggs a day after maturation, which develop into creamy white larvae in 3-4 days. The larvae live in similar environments but are rarely seen. Some species show parental care to the larvae. In general, it is an agile insect with well-developed wings (Pohl *et al.*, 2008). Although jewel beetles live in tropical regions, they are easily recognized by their bright metallic coloration. Many of these species attack dead trees and use the remains, thus ensuring the decomposition of dead wood. They contribute to ecology with this behavior (Evans *et al.*, 2007; Al-Jahdhami, 2021). Moreover, pine sawyer beetles are a wood-boring insect. It is widely distributed in North Africa and Europe. It got its name from the fact that it generally colonizes in pine trees. The eggs hatch into larvae inside the shell. Then they enter the heartwood part and become pupae. Young adults feed on pine sprout bark. While they require 2 years in northern latitudes, they complete their life cycle in 1 year in Southern Europe (Naves *et al.*, 2008; Pajares *et al.*, 2010). Naves *et al.* (2008) reported that the sizes of adult insects vary depending on the region of the tree. For example, they noted small insects (about 2.2 cm) on the upper branches of the tree and larger insects (about 20.6 cm) on the trunk bolts. Lucanidae beetles (stag beetles) live in decaying wood and feed on cellulosic material. When females find a suitable log to lay eggs, they decide the number of eggs according to the quality of the log. If there are no different species (termites or insects) in the log, it is a potential habitat as a moist and soft area. Larvae usually develop in 3 stages. While the first 2 stages take place within 2-4 weeks, the 3rd period varies between 6 months and 2 years according to the temperatures (Huang, 2018).

Passalidae beetles live in tunnels they dig into moderately rotten wood and are a family of shiny black scarabs ranging from 1-8 cm in length. The length of the tunnels can exceed one meter. The female or male initiates these tunnels, and then the opposite sex joins them. After mating occurs in the tunnels they dig, the eggs are laid in a nest made of thinly chewed trees. The larvae eat this chewed wood. Adults provide protection to the larvae until they reach the pupa stage. Their transition to adulthood takes weeks or months until they turn red brown to black. Sexually mature adults dig tunnels dug by their parents or migrate to form a different colony. Some species migrate by flying, some by walking (Ulyshen, 2018). Furthermore, the beetles of the Buprestidae family are characterized by a short, upturned head and biting mouthparts, often with oval or elliptical eyes that may protrude slightly beyond the outline of the head. These beetles have medium length antennae and are known for their elytra, which cover the abdomen and have either longitudinal grooves, rows of punctures, or keels. Buprestid larvae are segmented, flattened from top to bottom, and mostly glabrous with an enlarged thoracic area. They can be classified into several morpho-ecological types. Buprestids are often tree-oriented, relying on either weakened or healthy trees as their habitat. During periods of robust tree growth, the larvae may be hindered by tree defenses such as callus formation. However, when trees die, the phloem and xylem remain suitable for larval development for a limited period. The typical life cycle of buprestids is usually one, occasionally two, years. Adult beetles emerge in the spring, leaving distinct D-shaped exit holes in the bark of tree trunks and branches. Adults initially feed on foliage, pollen or nectar before females lay eggs either on the surface of the bark or in crevices. Following hatching, the nymphs move to the phloem where they feed and go through several phases of development (typically four) prior to winter. They pupate in the spring, just before the next emergence of the adult beetles (Evans *et al.*, 2007).

4 Economic importance of edible Coleoptera

Throughout history, people from various cultures worldwide have included insects in their diets, with over 2,000 insect species being consumed across 113 countries (Yen, 2009; Dobermann *et al.*, 2017). Insects such as beetles, caterpillars, and crickets are commonly eaten and provide a substantial source of dietary protein (Raheem *et al.*, 2019a). The Food and Agriculture Organization (FAO) has actively promoted insects as a viable food source, and the global market for edible insects is projected to surpass US $522 million by 2023 (Han *et al.*, 2017). In addition, the market for edible insects in the Asia-Pacific is forecast to grow to US $270 million by 2024 (Guiné *et al.*, 2021). Countries in Southeast Asia, such as Thailand, Laos and Cambodia, have seen a substantial increase in insect rearing and processing. Thailand has been a main contributor to insect-based products in the Asia-Pacific market since 2004, and currently holds a 12% of the global market share. Insect farming is widespread in Thailand, mainly in the Northeastern part of the country, where they consume around 7,500 tons of insects annually. This includes species sourced from neighboring nations like Myanmar, Laos, and Cambodia. The logistics and supply chain for the edible insect industry are well-established in Southeast Asia (van Huis, 2016; Krongdang *et al.*, 2023). Insects are usually sold as a cash income in some countries, for example in Netherlands, 50 g of yellow and lesser mealworms are sold for €4.85. In Thailand, red palm weevil/Sago palm weevil, dung beetle, scarab beetle/rhinoceros beetles and mealworm are sold for US $7.35-8.82/kg, US $0.30-1.50/each, US $11.76-14.70/kg and US $7.35-8.82/kg, respectively (Krongdang *et al.*, 2023). Trades in developing countries are diverse, but little is known about their establishment and development. Little accurate information is available on the number of insects bought and sold on the market due to the informal nature of this trade. The export of insects as a source of food to the western world is mainly driven by the demand of from Africa and Asia, or by the emergence of market for exotic foods (van Huis *et al.*, 2013). China and Myanmar are the main importers of insects. Their import value is more than US $800,000. Meanwhile, with a value of over US $200,000 in 2022, the United States of America, Japan, and the United Kingdom are the main countries to which insects are exported (Krongdang *et al.*, 2023).

However, the negative perceptions surrounding insects as food, often stemming from a fear of trying new foods (neophobia), hinder their adoption as mainstream culinary choices (Dobermann *et al.*, 2017). To address this challenge, efforts should focus on highlighting the practical advantages of consuming insects (Sun-Waterhouse *et al.*, 2016), offering information about their nutritional and environmental benefits, organizing events for tasting and education, and creating cookbooks featuring insect-based recipes. Additionally, making insects ingredients in familiar dishes could enhance their acceptance. Furthermore, the edible insect industry faces significant hurdles in ensuring safety, extending shelf life, standardizing insect farming practices, and implementing necessary government regulations (van Huis, 2016; Han *et al.*, 2017; Kim *et al.*, 2019). Estimated insect protein market size by country at the end of 2033 and global market size according to FMI Report (2023) are given in Figure 3a,b.

Insects are becoming an appealing choice for animal feed due to their high nutritional content, efficient use of space, and minimal environmental impact. They are already a natural part of many animals' diets (Veldkamp and Bosch, 2015). Using insect-based animal feeds can offer cost advantages compared to traditional feeds, which make up a significant portion of livestock production expenses (van Huis *et al.*, 2013). Promising candidates for large-scale insect-based feed production include black soldier flies, mealworms, silkworms, grasshoppers, and termites (Dobermann *et al.*, 2017). Research has demonstrated that insect meal can replace a portion of commercial feed in diets for broiler chickens and egg-laying poultry without harming their growth and performance (Awoniyi *et al.*, 2003). Additionally, insect-based feeds can even improve the taste of meat products. In regions like Asia and Africa, small-scale farms commonly use insects as fish feed, successfully replacing fish meal in the diets of various fish

species (Dobermann *et al.*, 2017). In summary, insects show substantial potential as a protein source for animal feeds to meet the growing global demand, but addressing health and safety concerns, such as anti-nutrient properties, is essential before mass production can occur (Dobermann *et al.*, 2017; Kim *et al.*, 2019).

With the world's population continuously growing, there is a substantial need for increased food production, which could strain our already limited natural resources, leading to issues like deforestation, environmental degradation, and increased greenhouse gas emissions. The livestock industry, which currently occupies about 70% of global agricultural land, significantly contributes to these problems, often causing environmental concerns such as water contamination and ammonia emissions (Fiala, 2008; Lange and Naka-

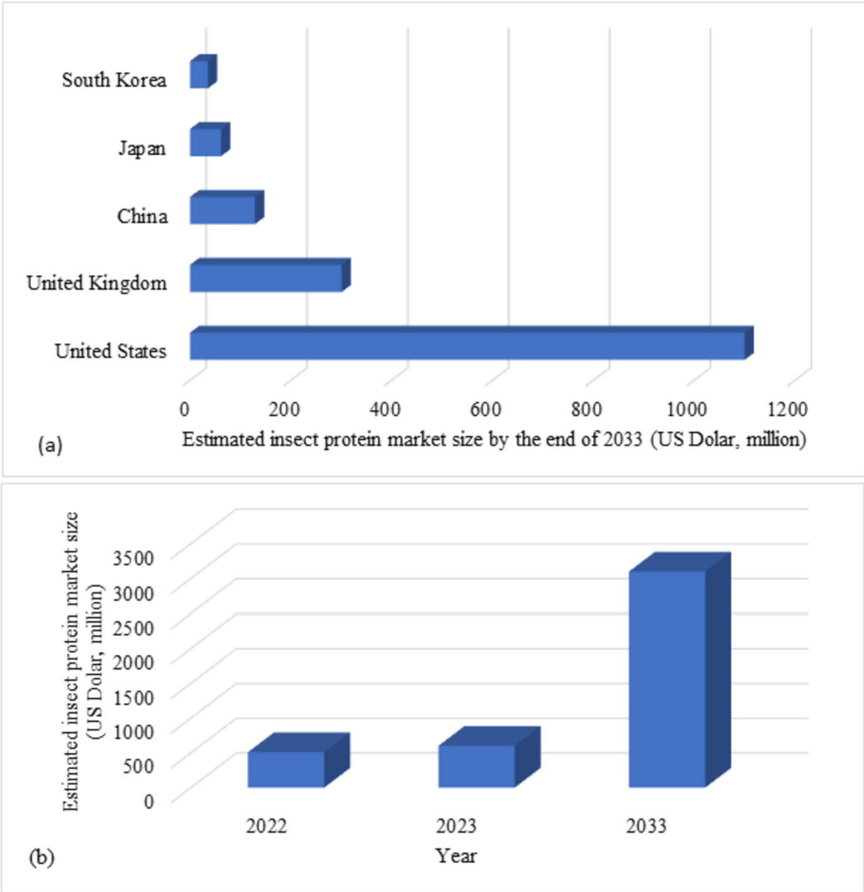

FIGURE 3 Estimated insect protein market size (a) by country at the end of 2033 (b) global market size (FMI Report, 2023).

mura, 2021). Producing insects for human consumption offers environmental benefits primarily because of their impressive efficiency in converting plant proteins into insect proteins, a process much more effective than observed in mammals.

Edible insects offer sustainability benefits because they can be raised on organic waste materials such as manure, compost, and human waste, which helps reduce environmental pollution (Bouchard *et al.*, 2017). This practice of using organic waste as insect feed also increases the profitability of insect farming. When it comes to GHG emissions, insects release far fewer GHG and ammonia into the environment compared to pigs and cattle. Livestock farming is a major contributor to greenhouse gas emissions, accounting for approximately 18% of total emissions, even surpassing the transport sector. Methane and nitrous oxide produced by livestock have a much greater impact on global warming than carbon dioxide (Lange and Nakamura, 2021). In contrast, the GHG emissions associated with breeding edible insects such as grasshoppers, crickets and mealworm larvae are roughly 100 times lower than those from cattle and beef production (Oonincx *et al.*, 2010). In this context, the waste produced by farm animals, including dung and ammonia (urine), contributes to soil nitrification and acidification. With respect to ammonia production, the larvae of locusts, crickets, and mealworms also release significantly less ammonia into the environment compared to pigs, with a tenfold reduction (Oonincx *et al.*, 2010; Lange and Nakamura, 2021).

As a negative effects of Coleoptera, for example, blister beetles can be a threat to animal feed, especially when they are present in hay fields and contain harmful substances. Animals such as cattle, sheep, goats, emu, and horses have gotten sick or even died from consuming hay infected with these insects. This problem has been exacerbated by the practice of conditioning hay, where squashes the beetles inside the bales of hay. Beetles can also serve as carriers of pathogens that harm both crops and livestock. For instance, the striped cucumber beetle is known to transmit a plant bacterium that leads to substantial crop losses. Managing bacterial wilt in crops often involves controlling these beetle vectors. The lesser mealworm beetle is another type commonly found in poultry houses. While it feeds on certain pests, it also transmits disease-causing bacteria and fungi, negating any potential benefits. In the realm of stored products, beetles are a significant concern, with over 600 species worldwide associated with these goods. These beetles can either directly damage and consume the crops being stored, or consume fungi or other animals that are part of the ecosystem of the crops being stored. The red flour beetle, a common stored product pest, is used extensively in genetic research due to its economic significance and ease of culture (Bouchard *et al.*, 2017).

Moreover Coleoptera, have significant impacts on human affairs, particularly as forest pests. The nature and effects of these pests vary depending on the country and region. For example, in Sweden, it's estimated that as much as 45% of the yearly wood volume is lost due to bark beetles, resulting in substantial economic losses. Some weevils, specifically those in the Scolytinae and Platypodinae subfamilies, are notorious for damaging trees by feeding on their phloem. Phloem-feeding bark beetles are notable for their inadvertent introduction to new regions, often through international trade. Certain countries, such as New Zealand, are particularly susceptible to these introductions. Additionally, there are wood-boring beetles and beetles that tunneling through the sapwood, causing weakening or death to their host trees. Certain beetles exhibit unique behaviors, such as ambrosia weevils that cultivate ambrosia fungi in their burrows. The emerald ash borer, originally from Asia but introduced to North America, has caused extensive ecological and economic damage by causing widespread decline and mortality in ash trees. Beetles can also act as carriers of harmful fungal pathogens in forests, with some outbreaks resulting in significant tree mortality. Understanding the diversity of beetles associated with trees is vital for the global forest industry, as these insects have diverse impacts on forests and ecosystems. However, many beetle species in this context remain inadequately studied and understood (Bouchard *et al.*, 2017; Evans *et al.*, 2007). As a positive effects of Coleoptera, beetles that feed on plants, have been effectively used worldwide to control the expansion of non-native plant populations. The seeds of non-native weeds have been shipped unintentionally around the world for hundreds of years, and the problem is growing with worldwide commerce, resulting in the rapid expansion of weeds in new regions. Biological weed control involves introducing and managing natural enemies to curb weed growth, providing an eco-friendly alternative to pesticides. Dung beetles, such as Scarabaeidae and Geotrupidae, play a crucial role in managing dung, facilitating its decomposition by burying it, which helps prevent water pollution, pasture deterioration, and the proliferation of pests. Their contribution to the economy is significant, as they prevent financial losses caused by the accumulation of livestock waste (Table 2). Beetles also serve as essential pollinators for both cultivated and wild plants, a process known as cantharophily. This mutual relationship between beetles and flowering plants has led to specialized adaptations in both, but the decline in native and non-native pollinators, driven by factors like pesticide use, habitat loss, and poor farming practices, poses a serious threat to global food security and biodiversity (Fenster *et al.*, 2004; Cave, 2005; Bouchard *et al.*, 2017).

5 Nutritional value of edible Coleoptera

Malnutrition is still a big problem over all the world. Some people are starving and some people are well fed but eat nutrient-poor foods. In both cases the body is not getting enough valuable nutrients. Foods containing high amounts of protein, vitamins, fiber, minerals, valuable fatty acid composition are essential for human nutrition. The world's growing population and decreasing amount of agricultural land have made it necessary to find new, reliable and renewable sources of protein. Edible insects are a good alternative to existing sources, with a valuable protein and a rich composition of nutritional composition (Figure 4). In fact, the consumption of edible insect's dates back to ancient times. Interest in edible insects shows an increasing trend regardless of region and culture (Kim *et al.*, 2022; Liceaga, 2022; Zhou *et al.*, 2022).

5.1 *Macronutrient content*

Coleoptera is the most populous insect order. The macronutrient content of edible Coleoptera is given in Supplementary Table S2. Protein and fat are the main components of Coleoptera and it is followed by fiber and ash. All species of Coleoptera contain significant amount of fiber. Even if they come from the same species, their nutritional value varies greatly because of differences in habitat (reared or wild), metamorphic stage, origin and diet of insects. The proximate species distribution of Coleopteran insects varies considerably among species as shown in Supplementary Table S2. (Rumpold and Schlüter, 2013a; Zielińska *et al.*, 2015). In terms of nutritional value, Coleoptera species generally contain high amounts of protein and fat (Supplementyary Table S2). Protein content ranges from 71.0 to 16.8%. The ranges of fat, ash, fiber and carbohydrates as follows: 56.06-6.14%, 11.8-1.0%, 32.0-1.96% and 51.6-3.6%, respectively. Hlongwane *et al.* (2020) were

TABLE 2 Economic importance of edible Coleoptera (Bouchard *et al.*, 2017)

		Economic importance
Negative effects	Agriculture	- Boll weevil damages cotton. - Blister beetles can contaminate animal feed. Farm animals eating this feed have been reported to become ill or die. - The striped cucumber beetle is a herbivorous insect that eats the cucumber family. - Meal worm beetles colonize chicken coops and feed on shed feathers and poultry food. They may also sometimes feed on dead, dying chicks. - They are one of the main problems of stored products.
	Forestry	- They cause tree death at levels like those caused by fire or commercial harvesting. - Bark beetles' nest and lay eggs in the phloem. The phloem of dead or dying trees is the characteristic habitat of bark beetles. - The emerald ash borer consumes the phloem of ash trees and kills them. - Scolytine beetles feed on the phloem of trees and are transported to new areas through intermediaries such as wood packaging. - Many Coleoptera species tunnel into the sapwood, which weakens or kills the tree. - Christmas beetle and leaf beetle are defoliators of eucalyptus trees. - Many damaging fungal pathogens of forests are carried by insects.
Positive effects	Biological control of weeds	- They are used to prevent the spread of non-native plant types.
	Dung removal	- Manure accumulation because of animal husbandry pollutes waterways and provides an environment for flies and other pests to live and spread. Dung beetles help decompose the manure by burying it in the soil to feed the larvae.
	Pollination	- All insect species are important for pollination of wild and cultivated plants.

reported the fiber content of Coleoptera's between 2-28% and fat content of edible insects as 1-67%. Insects are known to be a rich in protein source. However, there is also a reality called protein quality. Proteins are composed of 20 amino acids and 8 of these essential amino acids cannot be synthesized in the human body and must be obtained through food. At the same time, it has been determined that different species of Coleoptera also have rich amino acid composition (Table 3). Again, there is a significant variation between same species. Studies in the literature showed that different species of Coleoptera is rich in lysine as well as other amino acids. In addition, since arginine cannot be synthesized in the body and is essential for growth, especially in children, its requirement becomes more important. It could be seen that species of Coleoptera are rich in argine (Table 3). There are many publications on the functional and nutritional attributes of the protein content of various insect species. Unfortunately, the lack of standardized fractionation process methods is a major shortcoming (Hall *et al.*, 2017; Mishyna *et al.*, 2019; Zielińska *et al.*, 2015).

Fatty acid composition of Coleoptera is presented in Table 4. By consuming Coleoptera insects, large amounts of fat and valuable essential fatty acids enter the body. The composition of lipid and fatty acid content of insects are affected by sex, diet, species, environmental temperature and stage of life (Oonincx *et al.*, 2015). Linoleic and α-linoleic acids are essential fatty acids and cannot be synthesized in mammals and so that should be taken by diet. They are important for brain function and the nervous excitation system. Coleoptera species have certain amount of linoleic and α-linoleic acids (Table 4). Studies in literature have also reported that insects contain significant amounts of essential fatty acids (Lucas *et al.*, 2020; Zhang *et al.*, 2020; Orkusz, 2021). Saturated fatty acid composition range between 2.32-68.6% and it is highest for *Zophobas morio* (68.6%). Besides, monounsaturated fatty acid range changes as 2.51-71.4% (Table 4). At room tem-

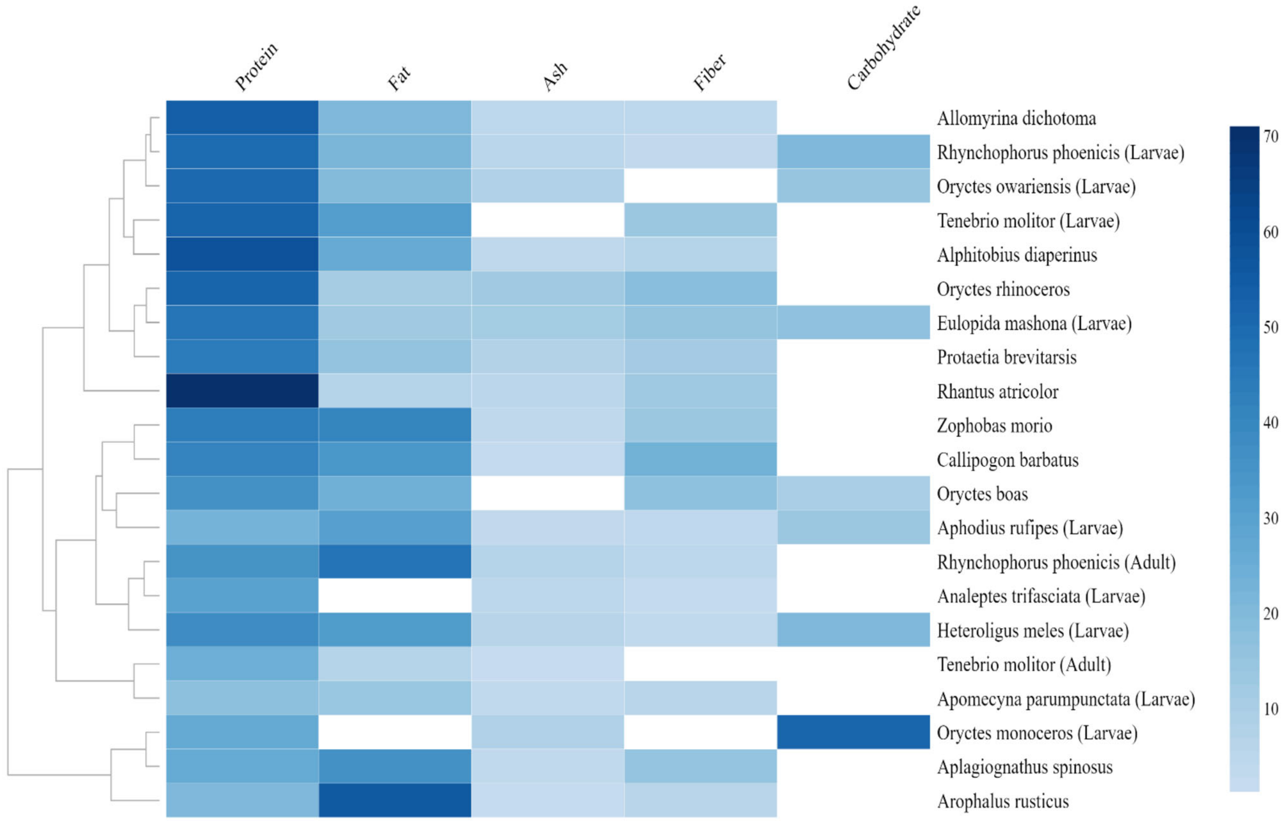

FIGURE 4 Heat map for chemical composition (% dry weight) of some Coleoptera species.

perature, most insect lipids are liquid. Therefore, they are referred to as insect oil. The fact that insect oils are liquid at room temperature enables their incorporation into many common foodstuffs such as fry oil, food grade lubricants and mayonnaise. At room temperature, some of insect oils are in solid form, so known as insect fats, and contains a significant quantity of saturated fatty acids and it is of interest for margarine, confectionery and pasta production systems (Ushakova *et al.*, 2016; Sosa and Fogliano, 2017).

It is a known fact that unsaturated fatty acids are beneficial for human health. As shown in Table 4, coleopteras are a rich source of unsaturated fatty acid composition. It is also known to be an important source of linoelic and linolenic fatty acid composition. It is also composed of other fatty acids. The diversity of fatty acids indicates the nutritional richness of the product. The fatty acid richness of Coleoptera is shown in Table 4.

5.2 *Micronutrient content*

Minerals play an essential role for a healthy and long life. They have many important functional roles in human body such as producing different hormones, building strong bones, regulating heart rate and transmitting nerve impulses. Mineral composition of Coleoptera species are given in Table 5. Coleoptera species are rich in Ca, P, Mg, Na and K. Some species of Coleoptera can full fill the requirements of daily intake of 4,700 mg/day for potassium while some of others cannot be. Maximum daily uptake value of sodium (1,500 mg) cannot be met with any 100 g Coleoptera species. On the other hand, iron is an important mineral for human body and its daily uptake range varies between 7.5-58.5 mg/day with respect to the women, man and premenopausal women (Rumpold and Schlüter, 2013a). Iron composition of Coleoptera species range between 1.0-30.80 mg/100 g sample (Table 5). It shows that about 100-150 mg Coleoptera insect consumption can meet the iron need according to the type of consumer.

Vitamin contents of Coleoptera species are presented in Table 6. Coleoptera insects contain a significant amount of minerals as well as a certain number of vitamins. Vitamin C intake of 100-200 mg/day will ensure adequate plasma levels (Spoelstra-de Man *et al.*, 2018). Depending on the type of Coleoptera insect, 100 g consumption of any Coleoptera defined in Table 6 covers about 1.2-14.88% of the daily required amount of vitamin C. It was expressed as recommended daily vitamin E intake age dependent and changes as 5-13 mg/day, 13 mg/day, 11 mg/day for for infants/children, men and women, respectively (Galli *et al.*, 2017). Consumption of 100 g of *Rhynchophorus ferrugineus* is sufficient to sup-

TABLE 3 Amino acid profile of Coleoptera species (mg/g protein)

Scientific name	Ile	Leu	Lys	Met	Phe	Thr	Tyr	Val	Arg	His	Cys	Trp	References
Allomyrina dichotoma	21.2	31.2	24.2	–	17.5	18.7	38.7	27.2	25.8	23.5	43.5	–	Ghosh *et al.*, 2017
Orytes rhinoceros (Larvae)	39.8	53.0	44.20	19.4	46.1	33.4	30.9	35.0	81.6	38.2	20.2	–	Rumpold and Schlüter, 2013a
Protaetia brevitarsis	16.2	23.1	17.5	3.1	16.2	15.5	33.0	24.9	20.9	18.2	26.3	–	Ghosh *et al.*, 2017
Rhynchophorus ferrugineus	8.0	12.0	11.0	2.0	7.0	8.0	21.0	10.0	10.0		1.0	1.0	Zhou *et al.*, 2022
Rhynchophorus phoenicis (Larvae)	24.0	47.0	42.0	12.0	–	28.6	5.1	41.0	–	11.0	10.6	–	Rumpold and Schlüter, 2013a
Sciphophorus acupunctatus (Larvae)	48.2	78.2	53.5	20.2	46.1	40.4	63.5	62.0	44.0	14.	26.7	8.1	Rumpold and Schlüter, 2013a
Tenebrio molitor	–	10.6	5.4	1.3	–	4.18	–	5.88	–	3.16	–	8.0	Lucas *et al.*, 2020
Tenebrio molitor	19.8	33.7	20.1	–	17.6	18.3	34.5	29.4	22.3	28.0	31.6	–	Ghosh *et al.*, 2017
Tenebrio molitor (larvae)	50.3	106.4	54.5	12.8	–	41.8	–	58.8	–	31.6	8.6	8.0	Rumpold and Schlüter, 2013a
Tenebrio molitor	21.6	45.8	26.7	9.6	16.1	26.1	28.8	39.7	25.6	16.1	5.5	–	Zielińska *et al.*, 2015
Zophobas morio	9.3	19.1	10.3	2.1	6.8	7.8	13.7	10.3	9.6	6.0	1.5	1.8	Zhou *et al.*, 2022
Zophobas morio	8.8	13.6	10.7	2.5	7.4	7.8	13.1	12.3	12.9	6.0	1.7	–	Orkusz, 2021

Abbreviations: Lys = lysine, Ile = isoleucine, Leu = leucine, Met = methionine, Phe = phenylalanine, Thr = threonine, Val = valine, Arg = arginine, Tyr = tyrosine, His = histamine, Cys = cysteine, Trp = tryptophan.

ply the suggested daily amount of vitamin E for women, men, children and infants. On the other hand, 100 g of any species of coleoptera does not meet the daily requirement of vitamin A (500-600 mg) (Hlongwane *et al.*, 2020). It was also stated that there are limited reports of vitamin content in insects for human consumption. Also, deviations from the existing results have been identified (Rumpold and Schlüter, 2013a).

5.3 *Comparison with other common protein source*

Many nutrients for human diet are found in nature in different proximate composition and some of them presented in Table 7. According to this table, duck carcass contains the least amount of protein, while Coleoptera can contain the highest amount of protein according to the type of species (maximum 66.0%). Similar situation is also observed in the amount of Coleopteran fat that has the highest value depending on the species type. Coleoptera has a significant amount of fiber that ranges between 1.96-22.90% and it is followed by nuts with the highest fiber ratio of 3.01%. Apart from Coleoptera, according to total energy content, chicken breast has the lowest rate (98.0%) and beef has the highest rate (542.0%) per 100 g of edible portion. Coleoptera, on the other hand, has a very high energy range of 282.32-652.30% (Orkusz, 2021; Zhou *et al.*, 2022). Note that the protein levels of plant sources, nuts, and eggs are lower than the protein levels of Coleoptera (Table 7).

6 Nutraceutical properties and medicinal uses of edible Coleoptera

Nutraceutical properties of a source related to health protection or treatment considered effective for the nutrients found in the food component. There are many reports expressing the active compounds of edible insects beneficial to human health. These bioactive substances can exert antioxidant, anti-inflammatory, antimicrobial, hypertensive, immunomodulatory and blood sugar effects (Aguilar-Toalá *et al.*, 2022). Comparison of essential amino acid content of various

TABLE 4 Fatty acids composition of Coleoptera species (g/100 g)

SN	$C_{10:0}$	$C_{12:0}$	$C_{14:0}$	$C_{15:0}$	$C_{16:0}$	$C_{17:0}$	$C_{18:0}$	$C_{20:0}$	SFA	$C_{14:1}$	$C_{16:1}$	$C_{17:1}$	$C_{18:1}$	$C_{20:1}$	MUFA	$C_{18:2}$	$C_{18:3}$	PUFA	References
A.m.	–	0.02	0.12	0.01	6.42	0.01	0.28	0.03	6.93	0	1.32	0.01	7.94	0.02	9.30	0.69	0.01	0.81	Ghosh *et al.*, 2017
A.d.	–	0	0.65	–	25.18		8.55	0.38			0.22		38.49	0		23.28	1.14		Lucas *et al.*, 2020
O.o.	–	–	2.5	–	0.2	–	0.2	–	3.1	–	–	–	5.2	–	43.6	45.5	–	50.9	Meyer-Rochow *et al.*, 2021
O.r.	–	–	3.5	–	28.7	–	2.1	–	34.4	–	–	–	41.5	–	45.9	14.1	–	19.7	Meyer-Rochow *et al.*, 2021
Z.m.	NA	<0.2	1.7	0.4	52.8	0.7	12.6	0.4	68.6	NA	0.7	0.6	66.0	NA	67.3	32.9	1.1	34.0	Finke, 2015
T.m.	NA	0.6	5.2	0.2	25.5	0.2	4.0	0.2	35.9	NA	4.8	0.2	66.4	NA	71.4	49.0	2.2	51.2	Zhou *et al.*, 2022
T.m.	na	0.21	2.63	0.16	18.0	0.19	3.84	0.17	25.32	nd	2.07	0.18	40.86	0.16	43.27	29.68	1.61	31.37	Zielińska *et al.*, 2015
T.m.	–	0.11	1.63	0.02	4.71	0.02	0.08	0.04	6.94	0.07	0.89	0.03	15.56	0.02	16.58	7.57	0.01	7.78	Ghosh *et al.*, 2017
T.m.	–	<0.02	0.29	<0.02	2.29	<0.02	0.39	0.03	2.32	–	0.35	0.03	5.39	–	2.51	–	–	–	Orkusz, 2021
T.m.	–	0.23	3.11	–	18.52	–	2.43	0	–	–	2.09	–	–	49.50	–	21.82	0.84	–	Tzompa-Sosa *et al.*, 2014
R.p.	–	–	–	–	32.40	–	0.3	–	38.9	–	3.30	–	30.0	–	43.40	13.0	2.0	17.70	Rumpold and Schlüter, 2013a

Abbreviations: $C_{10:0}$ = capric acid, $C_{12:0}$ = lauric acid, $C_{14:0}$ = myristic acid, $C_{15:0}$ = pentadecanoic acid, $C_{16:0}$ = palmitic acid, $C_{17:0}$ = heptadecanoic acid, $C_{18:0}$ = stearic acid, $C_{20:0}$ = arachidic acid, SFA = saturated fatty acids, $C_{16:1}$ = palmitoleic acid, $C_{17:1}$ = heptadecenoic acid, $C_{14:1}$ = myristoleic acid, $C_{18:1}$ = oleic acid, $C_{20:1}$ = eicosanoid acid, MUFA = monounsaturated fatty acid, $C_{18:2}$ = linoleic acid, $C_{18:3}$ = linolenic acid, PUFA = polyunsaturated fatty acid. SN = scientific name, *A.m.* = *Allomyrina dichotoma*, *A.d.* = *Alphitobius diaperinus*, *O.o.* = *Oryctes owariensis* (larvae), *O.r.* = *Oryctes rhinoceros*, *Z.m.* = *Zophobas morio*, *T.m.* = *Tenebrio molitor*, *R.p.* = *Rhynchophorus phoenicis* (larvae).

TABLE 5 Mineral content of Coleoptera species (mg/100 g)

Scientific name	Ca	P	Mg	Na	K	Cl	Fe	Zn	Cu	Mn	I	Se	References
Allomyrina dichotoma (Larvae)	123.40	860.69	283.56	148.38	1249.1	–	14.26	10.26	1.43	8.64	–	–	Zhou *et al.*, 2022
Analeptes trifasciata	61.28	136.40	6.14	–	–	–	18.20	–	–	–	–	–	Rumpold and Schlüter, 2013a
Orytes rhinoceros (larvae)	0.04	–	–	26.28	0.20	–	4.94	–	–	–	–	–	Rumpold and Schlüter, 2013a
Protaetia brevitarsis (larvae)	258.56	1140.4	327.60	211.60	2001.4	–	16.20	11.89	1.82	5.89	–	–	Ghosh *et al.*, 2017
Rhynchophorus ferrugineus	38.0	239.0	120.0	38.0	568.0	–	1.0	8.0	1.1	0.6	–	–	Zhou *et al.*, 2022
Rhynchophorus phoenicis (larvae)	54.1-208.0	352.0-685.0	33.60-131.80	44.8-52.0	–	–	14.70-30.80	26.50-15.80	1.60	0.80-3.50	–	1.60	Rumpold and Schlüter, 2013a
Tenebrio molitor (larvae)	78.42	1039.2	315.23	108.82	737.0	–	10.02	11.74	2.00	1.50	–	–	Ghosh *et al.*, 2017
Tenebrio molitor (larvae)	42.9	264-368	62-92	53.7	337.0	–	2.47	4.33-4.95	0.83	0.32	0.02	–	Orkusz, 2021
Tenebrio molitor (adult)	24.2	295.0	69	66.0	368.0	–	2.87	4.86	0.75	0.46	0.022	–	Orkusz, 2021
Tenebrio molitor	18.4	272.0	86.4	48.9	297.0	175.0	2.15	4.45	0.64	0.36	<0.01	0.01	Finke, 2015; Nowak *et al.*, 2016
Zophobas morio (larvae)	26.2	290.0	43.5	38.5	286	–	1.99	3.02	0.36	0.37	<0.01		Orkusz, 2021
Zophobas morio	17.7	237.0	49.8	47.5	316.0	152.0	1.65	3.07	0.36	0.43	<0.01	0.01	Zhou *et al.*, 2022
Zophobas morio	42.04	562.95	118.29	112.83	750.59	–	3.92	7.29	0.86	1.02	–	0.03	Rumpold and Schlüter, 2013a

Abbreviations: Ca = calcium, Mg = magnesium, P = phosphorus, Na = sodium, Cl = chloride, K = potassium, Fe = iron, Zn = zinc, Cu = copper, Mn = manganese, Se = selenium, I = iodi.

TABLE 6 Vitamin composition of Coleoptera species (mg/100 g)

Species	A	B1	B2	B6	C	E	References
Analeptes trifasciata	12.54	–	2.62	–	5.41	–	Rumpold and Schlüter, 2013a
Apomecyna parumpunctata (larvea)	–	–	–	–	–	–	Thomas, 2018
Orytes rhinoceros (larvae)							Hlongwane *et al.*, 2020
Orytes boas	8.5	–	0.08	–	7.59	–	Rumpold and Schlüter, 2013a
Tenebrio molitor (larvea)	–	0.1	0.85	0.81	5.4	–	Orkusz, 2021
Tenebrio molitor (adult)	–	0.28	2.32	–	14.88	–	Rumpold and Schlüter, 2013a
Rhynchophorus ferrugineus	–	–	–	–	–	18.8	Chinarak *et al.*, 2020
Rhynchophorus phoenicis (larvae)	11.3	–	2.2	–	4.3	–	Hlongwane *et al.*, 2020
Zophobas morio (larvae)		0.17	1.12	0.32	1.2–10.1	0.52	Orkusz, 2021

Abbreviations: A = vitamin A, B_2 = riboflavin, B_1 = thiamine, B_6 = pyridoxine E = vitamin E, C = vitamin C.

TABLE 7 Comparison of nutritional composition of different protein sources and Coleoptera insect expressed per 100 g of edible portion

Nutrient	Protein (%)	Fat (%)	Carbohydrate (%)	Fiber (%)	Energy (Kcal/100g)	References
Coleoptera	23-66	1.5-69.78		1.96-22.90	282.32-652.30	Rumpold and Schlüter, 2013a; Tuhumury, 2021
Beef	22.5	4.3	0	0	542	Wood, 2017
Chicken breast	21.5	1.3	0	0	98	Orkusz, 2021
Salmon	22.2	4.7	0	0	0	Liceaga, 2022
Plant proteins	22.37	6.12	12.03	2.39	186.42	Fresán *et al.*, 2019
Fish	16-21	0.2-5.0	0-0.5	0	0	Dawson *et al.*, 2018
Egg	19.87	8.15	13.91	2.57	202.11	Fresán *et al.*, 2019
Nuts	18.12	11.59	9.63	3.01	204.60	Fresán *et al.*, 2019
Pork	21.0	2.2	0	0	0	Liceaga, 2022
Duck carcass	5.78	13.04	0	0	140.63	Orkusz, 2021
Horse meat	21.5	2.5	0	0	109	Orkusz, 2021

Coleoptera species with common protein sources can be seen in Figure 5. As well as this, Table 8 summarizes the functional effects of active compounds from Coleopterans.

Antioxidant activity was the most commonly evaluated bioactivity in the majority of studies. Antioxidants are known as oxidation inhibitors. Antioxidants can be found in the natural structure of foods or may be added to foods to prolong the durability or lower the risk of health problems. Edible insects are high in protein. They are therefore considered to have great potential as a source of peptides with antioxidant activity (van Huis, 2021a). Yellow mealworms (*T. molitor*) have also been the focus of most studies. This insect is important for commercial use and large-scale commercial manufacturing and is currently permitted for use in consumer products in Europe (Rumbos *et al.*, 2020). Antioxidant activity was also observed in *T. molitor* using ultrasonic and pressure-assisted extraction. GC-MS characterization of substances with antioxidative properties primarily by phenolic substances in total extracts (Navarro del Hierro *et al.*, 2020b). The in vitro antioxidant properties of peptides found in *T. molitor* were found to be enhanced by heat treatments such as baking and boiling prior to digestion compared to raw insects (Zielińska *et al.*, 2017). Antioxidant activity of edible insect show in Figure 6.

Insects, as well as insect peptides and proteins, chitosan, insect oils and chitin, have a number of compounds with antimicrobial activity. Antibacterial peptides are the most prominent among them (Zhou *et al.*, 2022). The antimicrobial role of peptides and/or proteins is being studied in detail by researchers. While most of the insect antibacterial peptides and/or proteins have been reported to be effective against bacteria and/or fungi. Besides, some antibacterial peptides and/or proteins have also shown activity against some parasites. Antibacterial peptides/proteins are divided into four groups in the literature. These are: (1) peptides rich in cysteine (drosomycin and insect defensin),

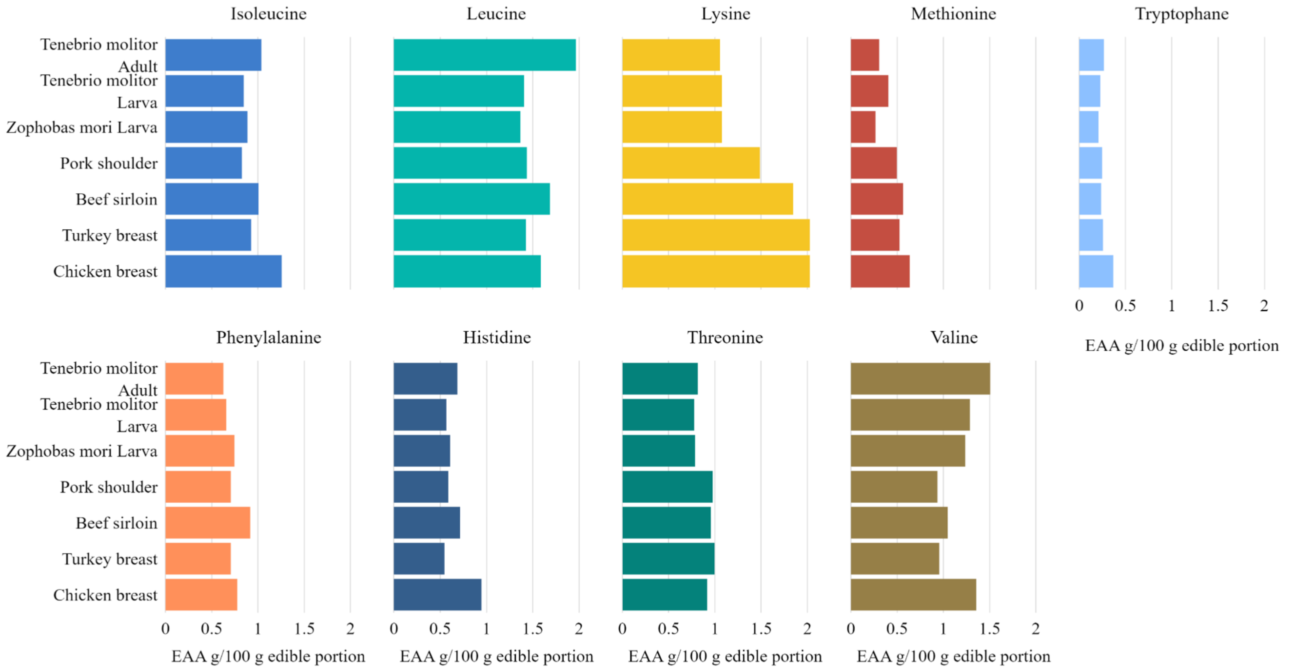

FIGURE 5 Comparison of essential amino acids content of Coleoptera species with various animal-based meats (EAA = Essential amino acids) (data obtained from Orkusz, 2021).

(2) peptides rich in proline (drosocin, lebocin and apidaecin), (3) α-helical peptides (moricin and cecropin), and (4) peptides rich in glycine (gloverin and attacin). Certain species of Coleoptera have insect defensins and defensin-like peptides with antimicrobial activity. These species are *T. molitor*, *Holotrichia diomphalia*, *Copris tripartitus*, *Zophobas atratus*, *Anomala cuprea*, *Oryctes rhinoceros*, *Allomyrina dichotoma*, *Acalolepta luxuriosa*. In addition, *Paederus dermatitis* and *Acalolepta luxuriosa* have cecropins and cecropin-like peptides, which are a family of cationic antimicrobial peptides of 31-39 residues (Yi *et al.*, 2014). It was expressed that antimicrobial peptides and other active compounds from insects have been tested and found that they can inhibit gram-negative bacteria, fungi and gram-positive bacteria. They also increase the number of probiotics, modulate the microbial community structure and regulate intestinal microorganisms (Zhou *et al.*, 2022). An in vitro digestion simulation model was used to determine the impact of flour of *T. molitor* on the gut microflora of humans, and it was observed that the proliferation of *Prevotellaceae* and *Bacteroidaceae* and the formation of short-chain fatty acids in the gut were strongly correlated with human body metabolites (de Carvalho *et al.*, 2019a).

Chitin, chitosan, and their derivatives are important products because they are believed to support various activities, including antioxidation, antihypertension, anti-inflammation, anticoagulation, antitumor, anticancer, and antimicrobial effects. The chitin content in the dry matter of *T. molitor* can be as high as 137.2 mg/kg. In addition, chitin can be utilized in significant amounts for the production of bioactive chitosan. Therefore, insects can be used as a novel source of chitin and chitosan (Kim *et al.*, 2022). Larvae of *T. molitor* contain high amount of chitosan and chitin, which are known to lower blood sugar and blood lipid levels. It is also known that chitin and chitosan support cholesterol metabolism, which increases the importance of *T. molitor* larvae in terms of health (Hahn *et al.*, 2020; Lucas *et al.*, 2021). It is also defined that antimicrobial, anti-obesity, anti-diabetic, antioxidant, anti-inflammatory are the main health benefits of chitin (Riaz Rajoka *et al.*, 2020).

Cell proliferation and unnatural growth of cells are typical features of cancer. Anti-tumor activity is an important property of insect derived functional compounds. Edible insects contain many functional substances with antitumor activity, such as sex attractant hormones, microelements, antimicrobial peptides, cordycepin, steroidal substances, chitosan, interferon, vitamins, etc., Anti-microbial polysaccharides and peptides found in edible insects support the human immune system and have antitumor activity (Qian *et al.*, 2022).

T. molitor is thought to be able to promote the regulation of the human immune system due to the presence of starch, cellulose, glycogen, chitin and pectin. Sup-

TABLE 8 Summarizes the functional effects of different species of Coleopterans

Scientific name	Extraction method or extract	Type of study	Efficacy	References
Tenebrio molitor	Saponins, proteins and carbohydrates	In vitro	Antimicrobial	Flores *et al.*, 2020
Tenebrio molitor	Supercritical CO_2 extract	*In vivo*	Immunomodulatory	Chen *et al.*, 2022
Tenebrio molitor	Ethanolic extraction	*In vivo* and in vitro	Antiadipogenic and obesity treatment	Seo *et al.*, 2017
Tenebrio molitor	Flour fermented with Lactococcus lactis strains	In vitro	Antioxidant and antihypertensive	Mendoza-Salazar *et al.*, 2021
Tenebrio molitor (larvae)	Pressurized-liquid extraction using ethanol and ultrasound-assisted extraction	In vitro	Antioxidant	Navarro del Hierro *et al.*, 2020
Tenebrio molitor (larvae)	Hydrolysis using gastrointestinal enzymes	In vitro	Antioxidant	Zielińska *et al.*, 2017
Tenebrio molitor	Hydrolysis using flavourzyme, protamex or alcalase	In vitro	Antioxidant	Messina *et al.*, 2019
Tenebrio molitor	Water and liposoluble extracts	In vitro	Antioxidant	Di Mattia *et al.*, 2019
Tenebrio molitor	Peptide	In vitro	Anti-inflammatory	Zielińska *et al.*, 2017
Tenebrio molitor (larvae)	Digestive peptidases of *T. molitor*	*In vivo*	Celiac disease treatment	Mlcek *et al.*, 2014
Curculio caryae	–	In vitro	Antibacterial	Shapiro-Ilan and Mizell, 2015
Green beetle (Mimela sp.)	Water-based extraction	*In vivo*	Antioxidant and Immunomodulatory	Tukshipa *et al.*, 2022
Blaps japanensis (larvae)	Blapsols A-D	–	Anti-inflammatory	Seabrooks and Hu, 2017
Holotrichia diomphalia (adult)	Tricin, palmitinic acid eicosane	–	Antifungal	Aidoo *et al.*, 2023
Allomyrina dichotoma (larvae)	Hexane, water, ethanol and ethyl acetate extracts	*In vivo*	Hepatoprotective and Anticancer	Lee *et al.*, 2015
Protaetia brevitarsis (Scarabaeidae)	Methanol extract	In vitro	Antioxidant	Suh and Kang, 2012
Holotrichia diomphalia (larvae)	Ethanol and petroleum ether extracts	In vitro	Antifungal (against *Pyricularia oryzae*)	Seabrooks and Hu, 2017
Hycleus oculatus (Thunberg)	(R)-(+)-palasonin Palasonin Palasonimide Cantharimide		Antitumor	Aidoo *et al.*, 2023

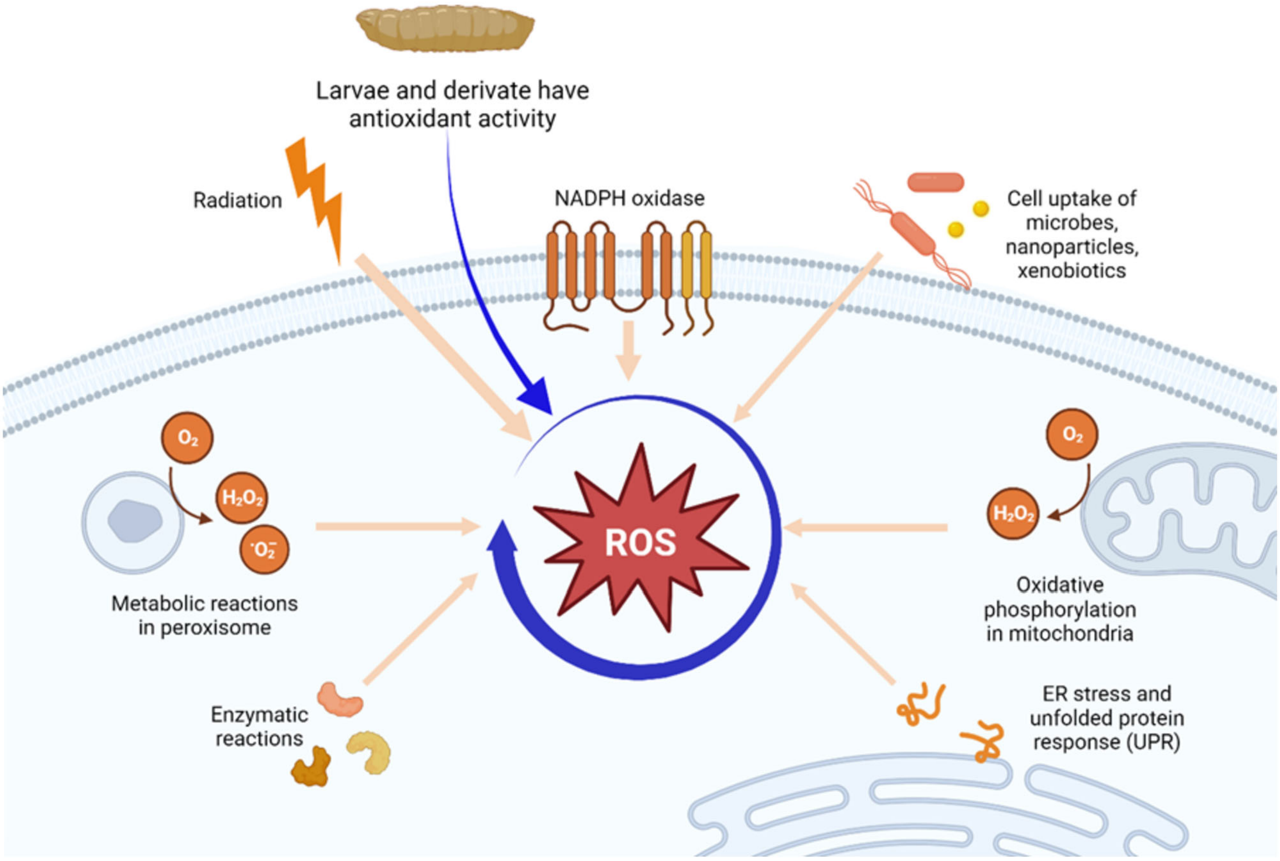

FIGURE 6 Antioxidant activity of edible insect active compounds.

porting the immunity of the human body is also considered as direct antitumor activity (Qian *et al.*, 2022). Vitamin B_{12} in mealworm larvae (*T. molitor*) was first reported in 2018, at a level of 1.08 g/100 g dry weight, which is an important vitamin due to its antitumor properties. In addition, studies have shown that *T. molitor* has effective antitumor activity due to its polysaccharide, trace element and vitamin (Schmidt *et al.*, 2019; Hahn *et al.*, 2020; Qian *et al.*, 2022). Fats and sugars from insects even have anticancer properties. Mealworm larvae oil was found to have inhibitory effects on colon adenocarcinoma (Caco-2) cells and in the treatment of human hepatocyte carcinoma (HepG2). Colon adenocarcinoma cells, with the proposed anticancer activity mediated through activation of the caspase-8, -9, and -3 death-dependent pathway (Wu *et al.*, 2020). Some chitin/chitosan, polypeptides, trace elements, polysaccharides, unsaturated fatty acids, vitamins, alkaloids, flavonoid, fibroin, insect hormones and other functional compounds of *T. molitor* were reported to be responsible for lowering blood pressure (Belluco *et al.*, 2013; Hahn *et al.*, 2020; Lucas *et al.*, 2021; Schmidt *et al.*, 2019). Besides, it has been reported that hydrolysates obtained from *T. molitor* exhibited inhibition of cyclooxygenase and lipoxygenase (Zielińska *et al.*, 2017). COX-2 and LOX have been implicated in the production of prostaglandins and leukotrienes. The excess levels of these compounds can result in deregulated inflammatory answers (Zielińska *et al.*, 2017).

Angiotensin I converting enzyme (ACE) is also responsible for raising pressure of blood. This is achieved by deactivating the bradykinin vasodilator or by transforming the deactive angiotensin I into the powerfull vasoconstrictor angiotensin II. ACE inhibition may have an antihypertensive effect as a result of the decrease in angiotensin II as well as the increase in bradykinin. It is possible that certain bioactive peptides with an aptitude for the adjustment of blood pressure could act as inhibitors of ACE (de Castro *et al.*, 2018). It was found that the purified peptide from *T. molitor* larvae (Tyr-Ala-Asn) had a successful antihypertensive effect in hypertensive rats by reducing systolic blood pressure (Dai *et al.*, 2013).

The high protein content of mealworm promotes the growth of *Prevotellaceae* and *Bacteroidaceae* bacteria, that provide benefits to the host through their saccharolytic and proteolytic functions (Anusha and Negi, 2022). Proteins from mealworms and their meal have been demonstrated to have a probiotic activity, and various pretreatments such as fermentation and hydrolysis have been shown to increase the intestinal health effect (de Carvalho *et al.*, 2019b). In vitro, protein from digested mealworm had a stimulating effect on the growth of *Prevotellaceae* and *Bacteroidaceae*, but no stimulating effect was observed on the growth of *Desulfuromonadales*, *Desulfovibrionales* or *Clostridium histolyticum* (de Carvalho *et al.*, 2019b). In another study, whey peptide extracts (1% w/v) from mealworms were used to study *Bifidobacterium* and *Lactobacillus* growth and found to stimulate growth (Yu *et al.*, 2016). In addition to the above-mentioned studies about the active constituents of insects on human health in vitro and *in vivo*, there is also a widespread use of them as medicinal support and medicine in cultural aspects throughout the world. *T. molitor* is known to be a Coleopteran mega family widely used as a medicinal insect in China. The intended use of *T. molitor* in China is usually cough, cancer, fever, rheumatism and inflammatory disorders. Blapsol is an active compound obtained from *T. molitor* (Seabrooks and Hu, 2017).

Cyclooxygenases are known to catalyse the translation of arachidonic acid into prostaglandins, which are essential medians of inflammation pain and fever. Five known dimers of dopamine from *Blaps japanensis* and Blapsols A-D were tested for activity towards cyclooxygenase (COX) enzymes: COX-2 and COX-1 and their efficacy was observed (Yan *et al.*, 2015). In traditional Argentinian medicine, Tenebrionidae is used for treatment of arthritis, HIV, cancer, diabetes, Parkinson's disease and asthma. The *Scarabaeidae* is a family of Coleoptera and make up 8% of its family and are often used for medicinal purposes (Seabrooks and Hu, 2017). In East Asia and China, *Holotrichia parallela* (*Scarabaeidae*), traditionally used as a medicine to cure superficial infections, tetanus, gout and rysipelas, has been studied for antioxidant capacity (Liu *et al.*, 2012). In China, the larvae of *Holotrichia diomphalia* (*Scarabaeidae*) are widely used as a crude medicine. The diseases for which it is effective are listed as contusion, edema and apoplexy (Seabrooks and Hu, 2017). The larvae of the beetle have been traditionally used as a medicine for the treatment of various liver diseases in humans (Lee *et al.*, 2015).

The larvae of *Protaetia brevitarsis* were also found to have liver-protective and antineoplastic properties. Hepatotoxic mice were used to study the effect of oral administration of powdered larvae of *Protaetia brevitarsis* and found that signs of chronic and acute liver injury were reduced (Lee *et al.*, 2014). The dung beetle *Catharsius sp*. (*Scarabaeidae*) is ground into a powder and orally ingested for the prevention of diarrhea, a common practice in northeastern India (Seabrooks and Hu, 2017). In Chinese, *Catharsius molossus* is a valuable insect with respect to the medicinal treatment. It is used for prevention of convulsions, relaxing the bowels, counteracting toxins and removing blood stasis (Lu *et al.*, 2015). *Meloidae* is a small family of Coleopterans with only 2,500 species. However, because of their protective excretions, the Meloidae have a very storied medicinal past. It is used for wart and cancer treatment in China and is known to have been used for therapeutic purposes since 1264. *Berberomeloe majalis* (*Meloidae*) is used for wart treatment in Spain. In Latin American, *Palembus dermestoides* (*Meloidae*) is applied for removel of rheumatism, ophthalmological problems and sexual impotence (Seabrooks and Hu, 2017). Also, macerated *Meloidae* is used as a head rub for the treatment of baldness in Mexico (Alonso-Castro, 2014).

Antinutritional factors from edible insects are substances that lower the nutrient efficiency of food and have a key role in the use of insects for human nutritions. Data on antinutrients are limited and even controversial compared to data on nutrients in edible insects. Most edible insects are herbivorous and hence feed on plants. The antinutrient content of edible insects varies widely. This is because insects feed on plants with different chemical compositions. The most common antinutrients found in edible insects are oxalates, phytates and tannins. Oxalates combine with magnesium and calcium to produce insoluble Mg and Ca oxalates, which result in kidney damage (stones in kidney) and low serum Mg and Ca levels. Phytate, restrict the taking of some essential minerals such as magnesium, calcium and iron. Tannins combine together with proteins and produce insoluble compounds which affects their bioavailability. High levels of tannin in the diet due to its astringent property, which is a consequence of its ability to bind to proteins in saliva and mucous membranes (Idowu *et al.*, 2019).

Phytate is one of the antinutrient found in edible insects and an important compound because its presence in foods reduces the bio-availability of minerals like iron, calcium, magnesium, copper and manganese. The phytate compositions of yam beetle (*Dinoderus porcellus Lesne*, Coleoptera: *Bostrichidae*) and palm weevil larva (*Rhynchophorus ferrugineus*, Coleoptera: *Curculionidae*) were expressed as 0.28 mg/kg and 0.289 mg/kg, respectively (Oibiokpa, 2017). Antinutrient content of all the growth stages of *Oryctes rhinoceros* was reported to be very low. The low levels of tannic acid, oxalate, alkaloids, saponins and flavonoids observed in the developmental stages of the palm beetle indicate that all stages are safe for human and animal consumption (Omosoto, 2018). *Rhynchophorus pheonicis* larvea has been reported to contain 1.4 mg/100 g, 0.6 mg/100 g, 1.0 mg/100 g, 0.9 mg/100 g and 0.1 mg/100 g of phytate, lectin, tannin, trypsin inhibitor and oxalate, respectively (Meyer-Rochow *et al.*, 2021). Low hydrogen cyanide (HCN), tannin and phytic acid levels were reported as 2.531, 0.481 and 0.276 mg/100 g and 2.651, 0.42 and 0.311 mg/100 g for palm weevils and yam beetles, respectively (Raheem *et al.*, 2019b). Oxalates are a naturally occurring substance that can be found in plants, animals and humans (Rahman *et al.*, 2013). Some researchers also claimed that amount of antinutrients in edible insects are in low concentrations and also could be similar in other food. However, note that the existence of antinutrients in insects is too important an issue to ignore. Further researches are needed to identification, control and elimination of these antinutrients. Awareness of which insect species contain which antinutrients is fundamental in this respect (Aguilar-Toalá *et al.*, 2022; Imathiu, 2020).

7 Safety aspects and risks related with consuming Coleoptera

The safety aspects of using insects as a food source continue to be viewed with scepticism by consumers. Some insects are inedible or cause allergic reactions, so all insects are not safe for consumption. The source of safety concerns is due to some common hazards associated with the consumption of insects as food. These hazards are microbiological, allergenic, parasitic, or toxicological (de Castro *et al.*, 2018). Table 9 shows the hazards from different species of Coleoptera. Eating insects could result in two potentially dangerous microbiotas being introduced. These are inextricably linked to insects as part of their lifestyle, and the other comes from cultivating and processing and is then passed on (EFSA Scientific Committee, 2015). Insects have a complex microbial community. Viruses, fungi, bacteria, archaea, and protozoa may be present (Raheem *et al.*, 2019b). These microorganisms may be related to insects in both farming environments and in nature. It is believed that most microbes in or on insects are harmless to humans and are not likely to be a cause of deterioration in foods (Marshall *et al.*, 2016) (Figure 7) and allergen reaction potential of insect consumption show in Figure 8.

T. molitor, yellow mealworm, commonly contains the following genera of bacteria *Propionibacterium*, *Dermabacter*, *Actunobacillus*, *Exiguobcacterium*, *Brachybacterium*, *Serratia*, *Citrobacter* and *Clavibacter*. Definite foodborne pathogens i.e. *Listeria monocytogenes* and *Salmonella spp*. have not yet been isolated from the intestines of farmed yellow mealworms. *Escherichia coli*, *Streptococcus spp*., *Micrococcus spp*., *Bacillus subtilis Ehrenberg* and *Citrobacter intermedius Sledak* were also found in *Alphitobius diaperinus Panzer* taken within poultry houses (Raheem *et al.*, 2019b). Bacteria that cause food spoilage have also been detected. *Spiroplasma spp*. Has been found in larvae of mealworm, which has been linked to neurological disease in humans (Garofalo *et al.*, 2017). An insect study showed that *T. molitor* can have a high microbial load of 10^5-10^6 cfu/g (Mézes, 2018). The pathogens of insects are considered to be harmless to human (van Huis *et al.*, 2013). Also, high level of microbial contamination was found in the larvae of *T. molitor*, with average counts in excess of 7.6-8.8 log cfu/g (Vandeweyer *et al.*, 2017a,b).

Pesticide residue is another potential problem with edible insects. Pesticides are used in farming to protect against pests. It is a threat in insects harvested from the wild, but not for insects harvested in insect farms. In edible insects, various kinds of pesticides were found among herbicides, insecticides and fungicides (Poma *et al.*, 2017; Calatayud-Vernich *et al.*, 2018; De Paepe *et al.*, 2019). Also, it has been reported that yellow mealworms are found to contain pesticides (Gao *et al.*, 2014; Houbraken *et al.*, 2016). In another research, no pesticide residues found in yellow mealworms (De Paepe *et al.*, 2019). One study aimed to assess harmful chemicals in edible insects (including *T. molitor*) and found that some chemicals may be present in the cultivated insect. However, the contamination levels were comparatively minor and the chemical content was equivalent to or below the content measured in frequently used animal products (fish, eggs and meat) (Poma *et al.*, 2017).

Another serious problem for edible insects is heavy metal contamination. Plants are exposed to heavy metal contamination from soil and air. Edible insects that consume these heavy metal-contaminated plants are also being contaminated with heavy metals. Consumption of high quantities of heavy metals can cause serious health problems. Insect species, food source growth stage and growth environment all contribute to the heavy metal content of insects (Rehman *et al.*, 2018; van der Fels-Klerx *et al.*, 2018; van Huis, 2021a). *Rhynchophocus phoenicis* and *Anapleptes trifaciata* were found to contain copper, cadmium, lead and nickel (Aguilar-Toalá *et al.*, 2022). In EFSA Scientific Committee (2015), it was reported that larvae's of *Rhynchophorus phoeni-*

TABLE 9 Potential hazards from different species of Coleoptera

Scientific name	Growth stage	Hazard	References
Eulepida mashona	Adult	Oxalates, alkaloids, saponins and tannins were detected	Musundire *et al.*, 2016a,b
Rhynchophorus phoenicis (Skin)	Larvea/Adult	Associated microorganisms: Bacillus, Klebsiella, Pseudomonas, Saccharomyces, Serratia and Staphylococcus	Amadi *et al.*, 2014
Rhynchophorus phoenicis (Gut)	Larvea/Adult	Associated microorganisms: Bacillus, Enterobacter, Serratia and Staphylococcus	Amadi *et al.*, 2014
Rhynchophorus phoenicis	Adult	Associated microorganisms: Pseudomonas, Bacillus, Acinetobacter, Staphylococcus, Proteus and Micrococcus species	Ogbalu and Williams, 2015
Rhynchophorus phoenicis	Larvea and adult	Lead, zinc and calcium were detected	Banjo *et al.*, 2013
Rhynchophorus phoenicis	Adult	Associated microorganisms: E. coli, Staphylococcus spp., Klebsiella aerogenes	Opara *et al.*, 2012
Tenebrio molitor	Adult	Allergens were detected	Broekman *et al.*, 2016; Han *et al.*, 2016; Verhoeckx *et al.*, 2016
Tenebrio molitor	–	Bacteria detected	Li *et al.*, 2016
Tenebrio molitor	–	Pesticides	Gao *et al.*, 2013, 2014; Houbraken *et al.*, 2016
Tenebrio molitor	Adult	Total aerobic count was detected as 10^8 log cfu/g	Caparros *et al.*, 2018
Tenebrio molitor	Larvea	Associated microorganisms: Enterobacter spp., Lactic acid bacteria, Erwinia spp.	Osimani *et al.*, 2018
Alphitobius diaperinus	Adult	Toxins were detected	Camenzuli *et al.*, 2018
Alphitobius diaperinus	Adult	Associated microorganisms: Firmicutes, Fusarium, Aspergillus, Proteobacteria	Wynants *et al.*, 2018
Tenebrio molitor	Larvea	Aflatoxins were detected	Bosch *et al.*, 2017
Alphitobius diaperinus Panzer, Tenebrio molitor, Zophobas atratus	Larvea	Tropomyosin was detected	van Broekhoven *et al.*, 2016
Alphitobius diaperinus, Tenebrio molitor	Larvea/Adult	Dioxins and organochlorine compounds were detected	Poma *et al.*, 2017
Tenebrio molitor	Larvea	Cadmium was detected	van der Fels-Klerx *et al.*, 2016
Zophobas astratus/ morio and Tenebrio molitor		Viruses were detected	Eilenberg *et al.*, 2015

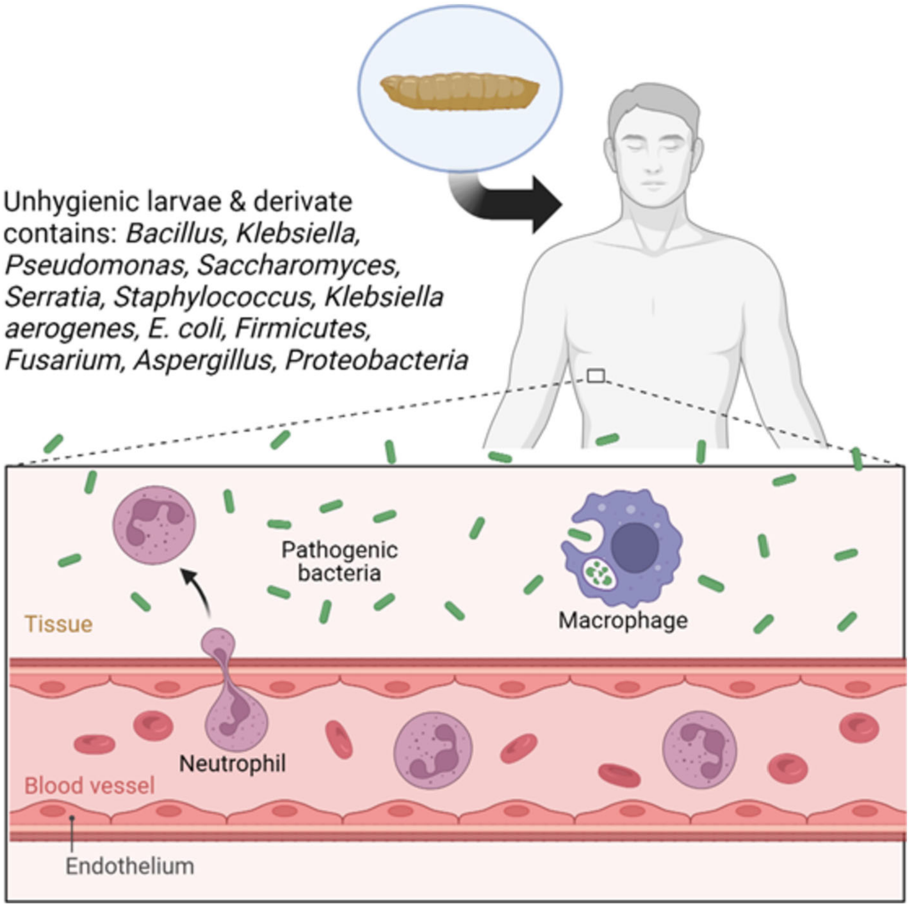

FIGURE 7 Potential of microbial infection form edible insect consumption.

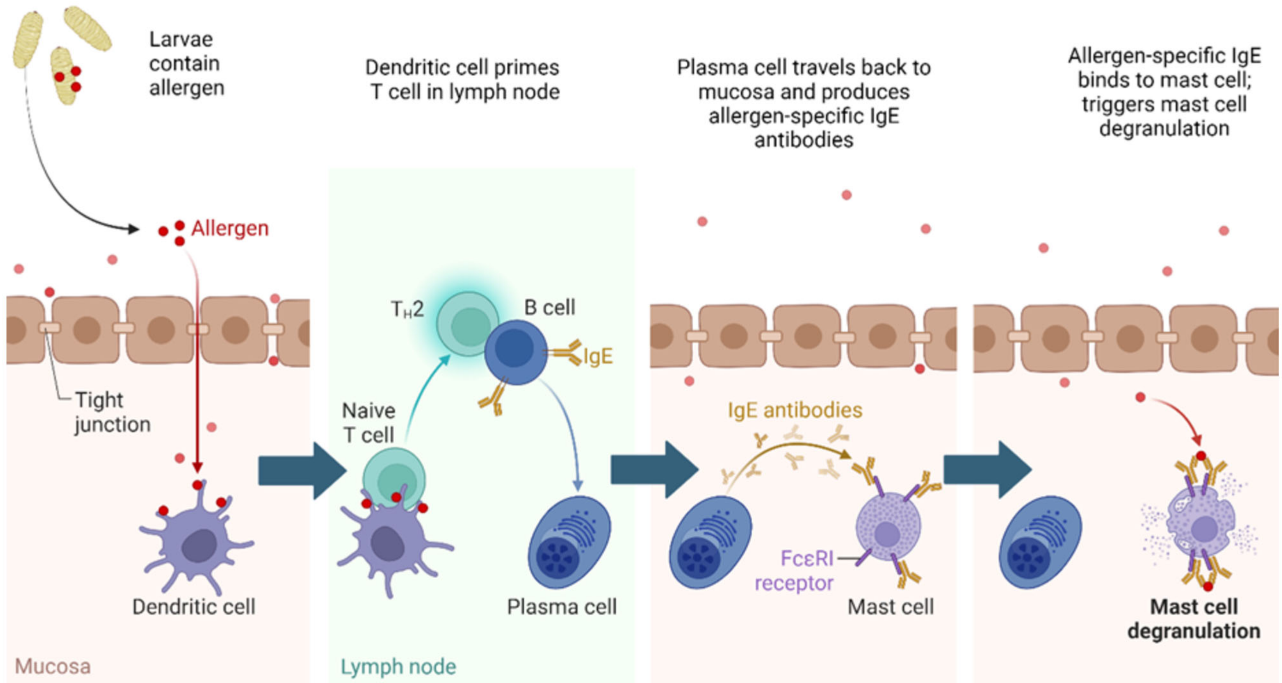

FIGURE 8 Allergen reaction potential of edible insect consumption.

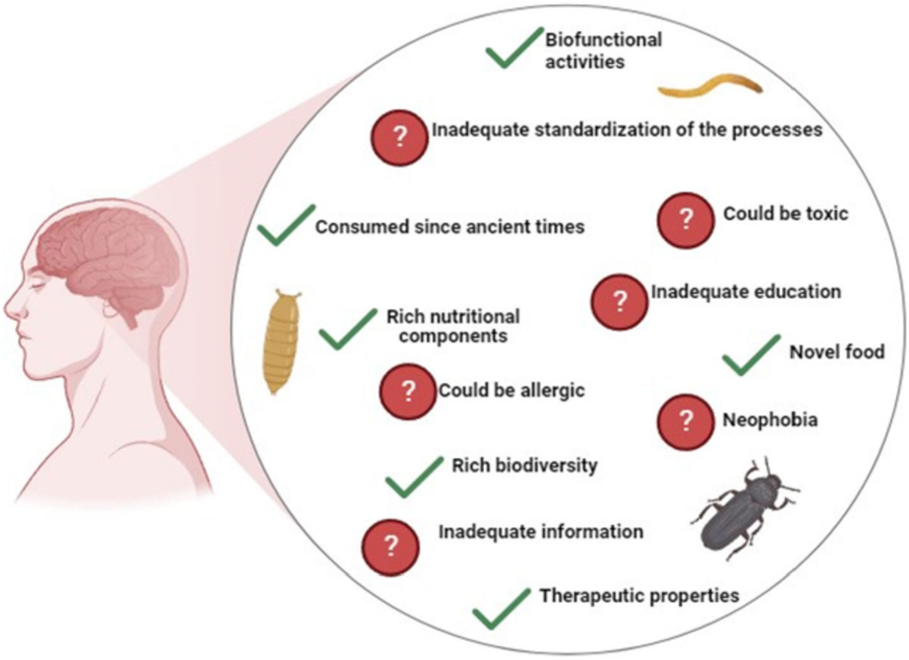

FIGURE 9 Factors influencing consumer edible insects' acceptance.

cis, *Rhinoceros beetle* and *Analeptes trifaciata* contain 0.02-0.03 mg cadmium/kg dry matter weight and 0.03-0.06 mg lead/kg dry matter weight. Maximum cadmium concentrations in animal products are 0.05 μg/kg wet weight for meat from cattle, pigs, poultry and sheep to 1.0 mg/kg for kidneys, cephalopods and bivalve molluscs. The maximum concentration of lead was defined as a range from 0.1 mg/kg wet weight for meat from sheep, poultry, pigs and cattle to 1.5 mg/kg wet weight for cephalopods and bivalve molluscs (EFSA Scientific Committee, 2015).

It has been reported that Spanish fly (*Lytta vesicatoria*) can synthesize cantharidin, which is a toxin. Tenebrionidae that are known as Darkling beetles produce alkanes and quinones. On the other hand, there has been a study where rats were fed with *T. molitor* larvea (dried powder form) for 90 days and no adverse effects were found in terms of toxin poisoning despite being given at the maximum daily recommended dosage of 3,000 mg/kg body weight/day (Schlüter *et al.*, 2017).

7.1 *Consumer acceptance of edible Coleoptera as human food*

The consumption of edible insects is also considered a traditional and/or cultural behavior in some countries in Latin America, Asia and Africa (Reed *et al.*, 2021). Although eating insects is considered a cultural practice in tropical countries, some insect species are consumed only in certain communities, regions, and/or by certain ethnic groups (van Huis *et al.*, 2021a). Despite the positive human health impacts of insects and their reputation as an environmentally sustainable food, acceptance of their consumption is low in Western countries (Nowakowski *et al.*, 2022). Lack of knowledge about edible insects and/or opposition to cultural norms are the main factors of neophobia which is a tendency to reject consumption of edible insects. Some survey based on insect neophobia over the past few years have supported these results (Megido *et al.*, 2016; Lambert *et al.*, 2021). Also, it was defined that the main reasons that make the edible insect acceptance difficult for people are: the perception of not consuming an object with a negative preconception in their mind and/or the inability to accept a food they have never encountered before (van Huis, 2021a). There are several opinions that have influenced consumer acceptance of edible insects. These are simply defined in Figure 9. At present, more than 80 countries, more than 2,000 species of insects are under consumption. Coleoptera genera are the most consumed insects, accounting for 31% of total consumption (Żuk-Gołaszewska *et al.*, 2022).

The eating insects as an ingredient is more acceptable than the consumption of the whole insect. All available insect-based foods are high priced because of production limitations. However, they can be made economical by increasing production (Reed *et al.*, 2021). It has been observed that people are more likely to consume edible insects when they are served in different food forms, such as energy bars, sandwich spreads, burgers and cookies, among others (Megido *et al.*, 2018).

It was also defined that unrecognizable form of edible insects are more applicable to Europeans and North Americans (Melgar-Lalanne *et al.*, 2019). In one study, lentil and beef burgers and their equivalent versions with 50% insect (mealworm) were prepared and evaluated hedonically. These tests were reported to reduce insect neophobia (Megido *et al.*, 2016). A series of sugary and savory insect-based foods were prepared and actually tasted by consumers and found that sugary preparations (i.e. crispy mealworms coated in chocolate) were more liked than the others (Megido *et al.*, 2014).

Existing studies on consumer acceptance of edible insects have focused on consumers' attitudes towards general edible insects that are not specific to a species. Therefore, there is not enough information in the literature on consumers' interest in the consumption of edible insects of the Coleoptera. On the other hand, although there is a community of consumers with food neophobia, there is also a significant community of neophilic consumers (positive towards new foods and open to experimentation). In order to increase consumer acceptance of edible insects, consumers need to be adequately educated and informed. In addition, the neophilic consumer community should be actively engaged to overcome insect neophobia.

7.2 *Safety measures to reduce risks*

The European Food Safety Authority indicates the presence of biological and chemical contaminants from insects are due to the inappropriate production methods, insect species, harvesting stages, substrate (feed) processing methods, and harvesting steps (EFSA Scientific Committee, 2015). In terms of safe consumption, insects in wild may contain high amounts of heavy metals. This is a risk factor for consumption. In other cases, wild edible insects are highly sensitive to pesticide and other chemical contamination (Zhou *et al.*, 2022). In many parts of Latin America, Africa, and Asia, people eat insects in whole form. Insects are generally roasted, dried, and fried or boiled before being incorporated into various dishes (Melgar-Lalanne *et al.*, 2019). Interest in semi-domestication of insects and farming them indoor is growing among the commercial community. As of today, only a few species of Coleoptera can be regarded as completely domesticated, such as the flour beetle and the flour worm, which are regarded as semi-domesticated (Vantomme, 2015).

While existing regulations have established optimal guidelines for the rearing, processing and storage of insects, it's important to recognize that many edible insect species have not undergone comprehensive microbiological safety evaluations. These insects carry the potential risk of introducing biological hazards, including bacteria known to cause foodborne illness. Insect-based foods are susceptible to contamination at all stages of production, distribution and consumption. There is also a tendency to overlook other biological risks associated with insect farming, such as the use of organic residues and food wastes to feed insects. Addressing these multiple concerns is critical to ensuring the safety and sustainability of the edible insect industry (Feng *et al.*, 2018; Grabowski and Klein, 2017a; Lähteenmäki-Uutela *et al.*, 2021; Niassy *et al.*, 2022).

Notably, the populations and microbial prevalence may differ between cultivated and wild insects. Production environment of the insects and the type of food they eat largely account for these differences. Therefore, appropriate farming methods need to be used to manage pathogens (Marshall *et al.*, 2016). In addition, some researchers are exploring ways to improve the safety of edible insects and reduce potential risks. Their efforts are focused primarily on refining cooking techniques, optimizing extraction processes, and improving insect rearing methods. The cooking method is a critical step in reducing or eliminating the microbial content of edible insects. For example, researchers conducted a study on *T. molitor* to evaluate its microbiological quality in fresh, cooked and fried forms. In its fresh state, no pathogenic microorganisms were detected, although spore-forming bacteria and *Enterobacteriaceae* were found. Boiling the insects for 5 minutes effectively eliminated *Enterobacteriaceae*, but didn't completely eradicate spore forming bacteria. It was also observed that insects boiled and stored at temperatures between 5-7 °C remained stable for over two weeks. Notably, roasting did not result in the destruction of *Enterobacteriaceae*. Therefore, it was recommended that insects be boiled for a few minutes prior to roasting to ensure microbiological safety (Klunder *et al.*, 2012). In a study, it was defined that the microbial load of mealworms must be minimized during the food production process in order for them to be eaten whole. The production of mealworms should be carried out in accordance with the general good hygiene and production practice standards and specific hygiene rules for food of animal origin (Osimani *et al.*, 2018). In the context of working with insects, extraction is an essential method. For fractionation or enzyme extraction when processing insects, it's important to recognize the initial high levels of microbial contamination. This contamination must be effectively reduced to acceptable levels by appropriate processing methods, including heat treatment (Schlüter *et al.*, 2017).

The lack of regulations and legislation on edible insects in international standards poses a significant risk to the safety of consumption. Standards for proper rearing, hygiene and storage should be established. Appropriate processing and decontamination methods against microorganisms during collection and storage should be determined and necessary measures taken to ensure food safety (Meyer-Rochow *et al.*, 2021).

7.3 *Regulatory aspects of Coleoptera consumption*

It has been proven through research that edible insects are rich in nutrients like minerals, protein and fat, and could be considered as an 'alternate' food source. Food allergy is an important consideration when eating edible insects. It can be a serious problem, especially for sensitive individuals who are allergic to crustaceans. Due to the need at this point in time, a number of legal regulations have been established about edible insects. In a study, the legal regulations on edible insects were examined in various nations such as China, Canada, European Union, Australia, United States of America. Every country has its own legal requirements for edible insects, but each country's regulations vary. The fact that different countries have different restrictions on edible insects is an important factor limiting the international consumption of these products (Lähteenmäki-Uutela *et al.*, 2021).

In 2021, the member states of the EU will vote and will be allowed to use the proteins from the lesser mealworm and the yellow mealworm as animal feed. In 2021 and 2022, EU member states will be allowed to use insect products from frozen, dried and powdered forms of the yellow mealworm as food (van Huis, 2022). A list of insect species with potential feed and food uses in Europe has recently been recommended by EFSA, which includes Coleoptera species such as *T. molitor*, *Zophobas atratus* and *Alphitobius diaperinus* (EFSA Scientific Committee, 2015). The European Food Safety Authority completed its assessment of the application for recognition of mealworm larvae as a novel food in November 2020. In the opinion expressed, mealworm larvae can be used whole, dried and ground for snacks. Ground and powdered mealworm larvae can be used in various other foods such as energy bars, baked goods, pasta, etc (Skotnicka *et al.*, 2021).

8 Culinary uses of edible Coleoptera

Numerous applications of edible insects including Coleoptera have been employed in culinary industries. The mealworm has been granted a favorable evaluation by the European Food Safety Authority (EFSA) as a novel food, making it the first insect species to achieve such recognition (Lotta, 2019). Based on the EFSA assessment, it has been determined that the consumption of whole insect larvae, which have undergone thermal drying processes such as blanching or oven-drying, as well as being transformed into powder form through drying and grinding, is deemed suitable for consumption by all demographic groups. Furthermore, these insect larvae can be included in various food products including snacks, pasta, and cookies (Lotta, 2019). According to De Oliveira (2017), the 10% of the enrichment formulation had the best nutrient-rich qualities, including higher protein and fiber levels, as well as an acceptance level exceeding 75%, making edible insects as the best choice in culinary uses (de Oliveira *et al.*, 2017). In addition to *Tenebrio Molitor* (*T. molitor*) (Coleoptera: Tenebrionidae), commonly known as mealworms, crickets (*Acheta domesticus*) and black soldier fly larvae (*Hermetia illucens*) are among the insects most commonly utilized for human food production. Meat substitutes have used these insects in a variety of proportions (10-60% and even 100%) and ways (ground, defatted, and acid-hydrolysed) (Kim *et al.*, 2017; Pintado and Delgado-Pando, 2020). In these subsequent sections the culinary uses of Coleoptera were discussed in terms of their traditional dishes, modern application as well as the preparation methods.

8.1 *Traditional dishes that uses Coleoptera as an ingredient*

Traditional foods are those that a community accepts as desirable and suitable food sources via habit and tradition. Traditional foods play a significant role in diets around the world and can be found regionally and within a specific natural setting through farming or wild collecting (Jia *et al.*, 2023). Insect consumption is a common element of the traditional diets of people in Latin America, Asia, and Africa. However, their acceptance as food ingredients is still low in Europe and USA (Raheem *et al.*, 2019b). Due to the scarcity of traditional foods like meat, fish, and chicken, insects are a key source of protein. However, another reason for their capture could be attributed to their high value as food sources, often considered delicacies. (Liceaga, 2022). The larvae of the genus *Rhynchophorus* (Coleoptera:

Curculionidae), commonly known as 'palmworms', have long been recognized as a significant dietary component in tropical regions (Rodríguez-Ortega *et al.*, 2022). In the culinary preparation of larvae, the initial step involves making an incision in the body to extract a fatty liquid, followed by the customary method of frying. The larvae can also be prepared using methods such as stewing, grilling, or roasting. The condiments that were incorporated into the dish consisted of onion, pepper, and salt (Rodríguez-Ortega *et al.*, 2022). Numerous African culinary publications feature recipes incorporating *R. phoenicis*, such as the renowned work 'La Cuisine Camerounaise' authored by Grimaldi and Bikia (1985). Notably, this cookbook presents a particular culinary creation whereby the aforementioned ingredient is prepared within coconut shells (Aneni, 2022). In order to maintain the integrity of the larvae, a recommended approach involves suspending them and allowing them to desiccate beneath a trellis structure. The practice of incorporating dried larvae into squash seed paste is frequently observed. Many Amerindian cultures rely on significant but undervalued food supplies that are provided by invertebrates that consume leaves and trash. Essential amounts of animal protein can be obtained by eating invertebrates, particularly during times of scarcity for fish and game (Dolganyuk *et al.*, 2023; Ocha *et al.*, 2022). For instance, the Guajibo, who inhabit Alcabala Guajibo in the Amazonas region of Venezuela, rely primarily on the larvae of the palm weevil *Rhynchophorus palmarum* (Coleoptera: Curculionidae) (Pimentel *et al.*, n.d.; Paoletti *et al.*, 2000b). Over 60% of their animal protein in the period spanning from July to August (raining seasons) comes from insects. Amerindians chose their animal food from the food webs in the rainforest that have maximal energy flow, and which form the most renewable store of readily available nutrients by choosing these little invertebrates. The ingestion of invertebrates that eat leaves and litter by people who live in forests as a source of protein, fat, and vitamins opens new possibilities for the growth of sustainable animal food production (Skotnicka *et al.*, 2021).

8.2 *Modern culinary applications*

The move toward Western foods poses a danger to entomophagy in cultures where edible insects are common components of traditional diets. Many urban dwellers find it challenging to consume insects as food because they find them unappealing in their natural state (Acosta-Estrada *et al.*, 2021). To combat this, initiatives are being made to combine the ancient practice of consuming insects with more widely consumed meals (Tao and Li, 2018). *T. molitor* is a species of darkling beetle that is frequently eaten in Asia. Its larvae are known as mealworms (Turck *et al.*, 2021; Khanal *et al.*, 2023). Recent developments have led to the development of street snacks with entomological components, which are often formed of a flour and mealworm meal mix (Kim *et al.*, 2016; González *et al.*, 2019). Based on report by Hartmann *et al.* (2018) and Cicatiello *et al.* (2020), the items taste like insects but are packaged in the form of common snacks, like crisps (Hartmann and Bearth, 2019; Cicatiello *et al.*, 2020). If these treats can be developed further with effective promotion, great profits are anticipated. An earlier study found that a sneakier strategy could be necessary to encourage more individuals to consume mealworms on a regular basis: insects could be concealed inside convenient and easy-to-cook foods as seasonings (Seo *et al.*, 2020). The initial task for the study team was to comprehend the flavor profile of this insect. A comparative analysis was conducted to assess the olfactory characteristics shown by mealworms at different stages of their developmental process. All the stages comprised mostly volatile hydrocarbons, which evaporate and emit odors, despite some variations in the particular molecules. Raw larvae, for instance, smelled like delicious corn, shrimp, and moist soil. Additionally, Zieliska *et al.*'s research from 2020 showed that using mealworms from *T. molitor* as a substitute for some of the butter and wheat flour in shortcake biscuits could have positive effects on their quality (Zielińska and Pankiewicz, 2020). According to their investigation, mealworm flour enhanced the protein and ash contents of biscuits while lowering the carbohydrate content. On top of that, greater mealworm flour additions improved the antioxidant activity of the biscuits and helped to enhance the amount of slowly absorbed starch while lowering the amount of quickly absorbed starch. Apart from that, yellow mealworm was employed in one of the mouthwatering recipes on the Scoolinary Recipes website, which was Broccoli Pachikay Sauce, Persillade of *T. Molitor* by Palmiro Ocampo Grey (Palmiro Ocampo Grey, n.d.). More details about the various countries' long-standing custom and modern culinary application of eating Coleoptera insects as a delicacy are provided in Table 10.

8.3 *Preparation methods*

Conducting thorough research is vital to ensure that processing improvements and design approaches function similarly to those employed for conventional proteins. This is crucial for addressing the challenges and limitations connected with the integration of protein

TABLE 10 Modern consumption of Coleoptera insects as edible food cuisine across various countries

Scientific name and stage	Cuisine	Country	References/sources
T. molitor larvae	Snacks	China	Liu *et al.*, 2010
Analeptes trifasciata larvae, *Oryctes boas* larvae, *Oryctes monoceros* larvae, *Aphodius rufipes* larvae, *Rhynchophorus phoenicis* larvae, *Heteroligus meles* larvae	Larvae	Nigeria, Africa	Alamu *et al.*, 2013
T. molitor adult and larvae	Baked mealworms flavored with dried vanila, paprika, dunked in chocholate	Belgium	Caparros *et al.*, 2014
Rhynchophorus phoenicis larvae, *Phyllophaga nebulosa* larvae		Ghana, Africa	Anankware *et al.*, 2015
Alphitobius diaperinus larvae-Tenebrio molitor larvae	Freeze dried, insect powder, lollipop	The Netherlands	Melgar-Lalanne *et al.*, 2019)
Oryctes rhinoceros grub	Grub toasting and roasting	Western Kenya	Wanjala *et al.*, 2023
Holotrichia adults and larvae, *Paragymnopleurus aethiops* adults and larvae, *Xylotrupes Gideon* adults and larvae, *Tenebrio molitor* adults and larvae	Fried beetles (wild/ farm harvested source)	Thailand	Krongdang *et al.*, 2023
Alphitobius diaperinus, *Tenebrio molitor* larvae	Mealworm, parmesan and chive omelets, mealworm and mixed berry smoothie, snacks	United Kingdom	https://www.eatgrub.co.uk/
Tenebrio molitor larvae	Curry flavored mealworm, paprika mealworm	France	Buy Edible Insects for Appetizer Online (insecteo .com)
Alphitobius diaperinus, *Tenebrio molitor*	Insect burger, Chocolate bar, lollipop, vodka, protein mix, insect bar, bread, insect pasta tagliatelle	Germany	https://wuestengarnele.de Insect pasta tagliatelle | Plumento Foods

from insects into nourishment formulations. In general, edible insects are a very wholesome supply of fats, amino acids, and fibres (Dossey *et al.*, 2016b). The implementation of early education efforts and the adoption of transformative methodologies could facilitate the normalization of insect consumption within contemporary society. Given that insects may be handled by adopting techniques comparable to those employed for conventional proteins, there exists a substantial prospective market for insect-based food products that are suitable, enticing, safe, and possess enduring qualities (Liceaga, 2022). To effectively tackle the issue of food security in the year 2050 and mitigate the scarcity of food observed during worldwide epidemics, it is imperative to devise comprehensive strategies, it is imperative for individuals, scientists, and food service providers to recognize the importance of exploring the utilization of insects as viable protein sources (van Huis, 2020). The impact of various processing techniques on nutritional composition & lifespan of edible Coleoptera is demonstrated in Table 11.

Commonly employed methods for the preparation of edible insects include traditional cooking techniques such as frying, scalding, baking, grilling, broiling, and stewing. Typically, these items are consumed in their entirety, either in their raw or cooked state, or after undergoing processing, or as extracts (Liceaga, 2022). Other methods of preparing insects require a reliance on processing techniques that transform insects into unrecognizable forms, such as flours or powders, protein hydrolysates, and fermentable substrates, as an effect of the significant increase in attraction to the novel protein source and market expansion targeted toward Western cultures (Melgar-Lalanne *et al.*, 2019; Liceaga, 2022). The most often utilized technique for preserving and preparing edible insects appears to be the use of various drying processes. However, the stability and nutritional content of the insects will be affected differently by each drying technique. For instance, drying methods resulted in minimal modifications in the protein, lipid, and fiber content of yellow mealworms (*T. molitor*) (Kröncke *et al.*, 2019). However, compared to the other drying techniques, oven drying, microwave drying, fluidized bed drying, and drying with a vacuum lowered the protein solubility, whereas freeze-dried mealworms showed the greatest degree of oxidation of lipid (Kröncke *et al.*, 2019). Overall, it was claimed that vacuum oven and microwave drying techniques may replace traditional oven and freeze drying. The utilization of vacuum conditions throughout the microwave drying procedure did not yield any discernible benefits, as there were no significant alterations seen in the proximal and fatty acid compositions of the mealworms (Kröncke *et al.*, 2019). Lenaerts *et al.* (2018) and Van Campenhout (2018) conducted a study that revealed a notable disparity between freeze drying and microwave drying methods in terms of their effects on lipid oxidation in *T. molitor*. Specifically, freeze drying was found to significantly increase lipid oxidation, whereas microwave drying resulted in very minimal alterations to the protein, fat, and ash composition of the mealworms (Lenaerts *et al.*, 2018). To guarantee nutrient quality and product performance, there is still a need for the optimization of the drying process for edible insects.

Furthermore, there exists empirical evidence suggesting that consumers display heightened favorable reactions towards food products incorporating insects that possess a lower level of perceptibility (such as in the form of flour or powder) in contrast to those featuring insects that are readily identifiable (e.g. in a conspicuous form) (Gmuer *et al.*, 2016). According to sensory evaluation studies, a meal containing apparent insects were rated significantly less favorably in terms of their appetizingness and likelihood to be consumed than meals prepared using insect flours or protein (Tranter, 2013; Caparros *et al.*, 2014; Tucker, 2014; Schösler and de Boer, 2018). It is advisable to exercise precaution when employing terms such as "insect flour," since they have the potential to create a misconception among consumers regarding its culinary properties, which may not align with those of grain flours often used in cooking and baking (Dossey *et al.*, 2016b). In contrast to authentic flours, such as those derived from wheat, which predominantly consist of starches and fiber, with protein as a secondary component, insects are principally composed of protein, with fat and fiber (specifically chitin) following suit (Dossey *et al.*, 2016b). However, a notable instance of a process that allowed the inclusion of insects as enriching components in baked products and pastas is food extrusion. This technique is frequently employed in the creation of cereal-based meals with different kinds of flour (Carcea, 2020).

By successfully removing the protein from the hydrophobic chitin, the resultant amino acid hydrolyzed products or powdered proteins tend to exert a more pronounced influence on the functional properties of the protein (for example, dissolved state, emulsion, and frothing). The utilization of these amino acid hydrolysates, which possess excellent solubility, can be employed in culinary creation for various purposes such as protein nutritional supplements, emulsification and stabilization, and enhancement of flavor (Liceaga,

TABLE 11 The impact of processing techniques on the nutritional composition and lifespan of edible Coleoptera

Scientific name	Treatment	Main findings	References
Blanching			
T. molitor	Submerged in bath with boiling water for 40 s	- Not significant decrease of the protein and ash content - The water activity of fresh and blanched larvae was close to 1 - Vitamin b12 slightly drop	Lenaerts *et al.*, 2018
Alphitobius Diaperinus	Water-logged in bath with water at 90 °C till temperature touches 88 °C (5 min).	- Decrease in microbial count (4.0 log cfu/g), whereas, aerobic endospores persevered - Atypical microbes were recognized - A few mycotoxins mold observed	Wynants *et al.*, 2018
Oven drying			
T. molitor	Blanching: 40 s in boiling water Microwave-drying: 8, 10, 13, 16, and 20 min in 1.5 cm insect layer on 4-m conveyer, dried with 16 microwaves sources of 2 kW.	- The average water activities obtained from drying durations of 16 and 20 minutes were 0.16 and 0.23, respectively - Blanching combined with drying resulted in a significant reduction in the population of vegetative cells, but the number of bacterial endospores exhibited only a little decrease - The total viable counts for all samples reached a maximum of 3.4 ± 0.8 log cfu/g - Bacterial endospores have the highest level of resistance	Vandeweyer *et al.*, 2017c
Freeze drying			
T. molitor	The mealworm was frozen using a benchtop lab scale freeze-dryer at 0.2 mbar for a duration of 48 h. the mealworm then was milled and grist. Then they were sieved into fraction.	- Preserve the original larval length and diameter - Initial color was conserved - Lowest chitin concentrations in the small particle fraction - Higher fat contents in the fine particle fractions	Purschke *et al.*, 2018
Vacuum drying			
T. molitor	The mealworms were placed on two metal sheets in and were dried for 24 h at 60 °C.	- The protein, fiber and fat contents of the dried mealworms were found to be greater in comparison to the fresh mealworms - Water activity and moisture drop significantly	Kröncke *et al.*, 2018
Hot air drying			
T. molitor	The larvae were placed on the backing plate (60 × 80 × 2 cm) in the middle of the rotating convection oven. Frozen larvae were dried for 1 h at 120 °C at ventilation stage 2.	- The protein, fiber & fat contents of the dried mealworms were found to be greater in comparison to the fresh mealworms - Water activity and moisture drop significantly	Kröncke *et al.*, 2018

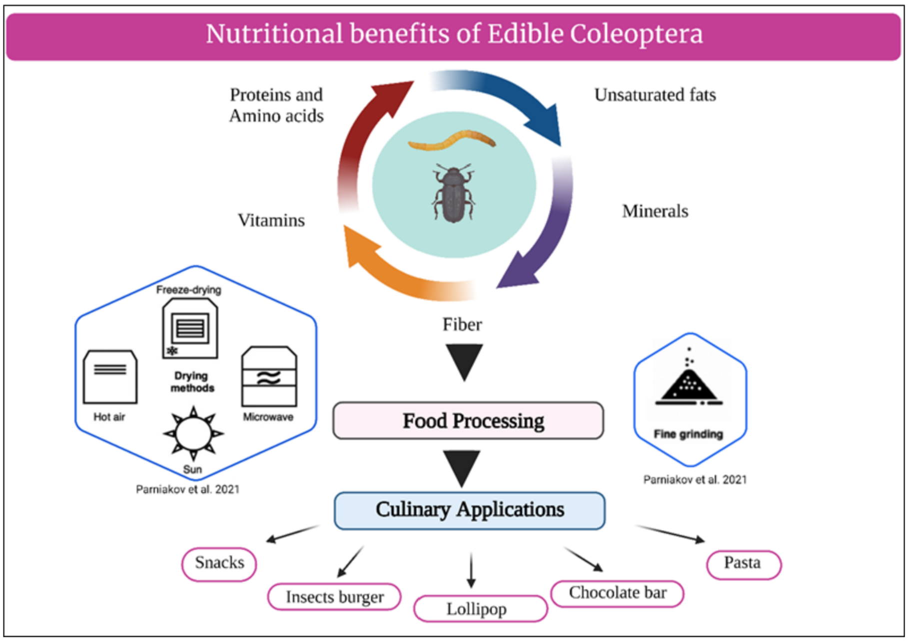

FIGURE 10 Depicted processing and culinary applications of edible Coleoptera species.

2019). The nutritious benefits of edible Coleoptera species, including processing and culinary uses, are shown in Figure 10.

9 Environmental benefits of consuming edible Coleoptera

Presently, a sizable portion of the planet's ice-free land is occupied by the livestock sector. Furthermore, it is considered one of the leading drivers of environmental degradation and global warming because to the harm it produces in soils and the discharge of organic matter, infections, and residues of drugs in products for human consumption (Ordoñez-Araque and Egas-Montenegro, 2021). For these reasons, it is critical to discover a moderate and perpetual solution to this issue. The ecological impact of conventional livestock systems is significantly influenced by the production of feed, and this holds true for insect production systems as well. The relationship between land usage and mealworm production is evident. For instance, Oonincx and De Boer (2012) found that the production facility for mealworms accounted for a mere 0.2% of the overall land use, whereas the feed utilized in this facility accounted for a substantial 99% of the land use (Oonincx and De Boer, 2012). In a similar vein, the water consumption directly attributed to the facility in question was only a portion of the overall water usage, which encompassed both rainfall and the water required for feed production (Miglietta *et al.*, 2015). According to these researchers, mealworms require two to three times less land and 50% less water per gram of edible protein in comparison to chicken. The production of one gram of edible protein from beef necessitates between 8 and 14 times more land and roughly 5 times more water when compared to mealworms (Oonincx and De Boer, 2012; Miglietta *et al.*, 2015). Apart from that, in relation to GHG emissions, it has been observed that mealworms exhibit a comparatively reduced environmental footprint when compared to conventional livestock systems. There is a significant disparity in emissions between broiler chickens and mealworms when considering edible protein. Broiler chickens are shown to have emissions that are 32-167% higher, whereas beef cattle release CO2 equivalents that are 6-13 times greater than those of mealworms (Oonincx and De Boer, 2012).

On the other hand, meat consumption, which is predicted to rise by 75% between the years 2005-2007 and 2050, is one of the primary contributors of this exploitation (van Huis 2015, 2022). Increasing agricultural productivity, consuming less meat, and finding substitute foods that necessitate minimal land and natural resources to produce them have all been suggested as remedies to this issue. Insects offer a promising alternative food source that may help to mitigate some of the environmental problems arising from the production of meat in Western countries (Lucas *et al.*, 2020). In comparison to traditional livestock agriculture, insect farming has a greater feed conversion efficiency, demands a significantly less financial investment, uses less water and space, and emits fewer greenhouse gases (GHG)

(Müller *et al.*, 2016). For instance, producing 1 kilogram of insect protein from various species of mealworm only requires 40 L of water (Abbasi and Abbasi, 2016). Additionally, insects have a large geographic spread and a rapid rate of reproduction (Gjerris *et al.*, 2016). A significant portion of the beetle fauna is represented by the family Scarabaeidae, order Coleoptera, suborder Polyphaga, and class Insecta, which includes scarab beetles (Piñero and Dudenhoeffer, 2018; Shah and Shah, 2022). Scarab beetles play a fundamental role in the terrestrial ecosystem both structurally and functionally. They act as natural scavengers by bringing in vast amounts of dung, which greatly purifies the earth's surface. Scarabs could bury human and cow feces into the soil by molding into spherical balls and root nodules (Sullivan *et al.*, 2016).

Since various environmental processes are spatially organized, spatial qualities are particularly crucial since they can be utilized to replace biotic dispersal, interactions, unmeasured ecological factors, and historical events (Tissiani *et al.*, 2017; Shah and Shah, 2022). Therefore, native settings, coupled with climatic and spatial courses, which alter assemblages of grassland and forest dwelling species at middle to wide spatial scales, are necessary for causative populations of environmental driving dung beetles and their purpose (Gotcha *et al.*, 2022). Dung beetles appear to be essential for maintaining ecological integrity in biological systems, specifically secondary seed dispersal and cycles of nutrients. Additionally, eating insects could reduce starvation in societies with little financial resources, which would considerably increase global food security (Lucas *et al.*, 2020). According to the UN and FAO (Perez Vázquez *et al.*, 2018), insects could be a viable solution to food insecurity that could result from population growth. Out of more than one million bug species, there are roughly 2,000 edible insect species. The number of edible insects will most certainly continue to grow thanks to ongoing study (Imathiu, 2020).

One of the foundations of food security is sustainability, which relies on existing generations' willingness to safeguard the ecological components that contribute to ensuring food security for forthcoming generations (Prosekov and Ivanova, 2018; Mbow *et al.*, 2019). Given that they can satisfy all dietary needs while using fewer resources than most meat-based proteins generated from livestock, insects are a viable and environmentally friendly food source for contemporary society in the 21st century. Despite its apparent simplicity, the process of eating is heavily contingent upon one's knowledge, comprehension, and capacity to adapt. The potential exists for a reduction in foodborne illnesses, assured food sovereignty, and improved dietary well-being for individuals lacking access to alternative sources of nourishment, if a greater number of cultures and individuals become aware of the advantages associated with insect-based foods and transition to regulated and monitored entomophagous diets (Matiza Ruzengwe *et al.*, 2022). Insects are commonly regarded as a favorable food source due to their ample supply of macro- and micronutrients necessary for optimal bodily functions, as well as the versatility of consuming different bug species at various stages of their life cycle. However, gaining market acceptance for a food extends beyond its nutritional value or potential environmental advantages. Consequently, a diverse range of Western food products derived from insects, such as grains, calories and protein energy bars, and dressings for salads, have been produced. The aforementioned encompasses the industrial inclination towards the domestication, cultivation, and production of food derived from insects (Baiano, 2020). Figure 11 shows an environmental benefit of consuming Coleoptera.

10 Cultural attitudes toward edible Coleoptera

There has been a spike towards interest in entomophagy within the past few years. The dietary consumption of insects as sustenance for humans is known as entomophagy (Town and Tranter, 2013). The demand to vigorously explore alternate sources of protein has prompted conferences and seminars to be held all over the world. Insect books and articles have been published in an effort to transform western perceptions of this food source, yet many westerners have an unfavorable perception of them. According to Yen (2009), the predominant attitudes about eating insects as food are either fear and disgust or curiosity.

This repulsive sensation leads to the widespread belief in western society that entomophagy is only a form of survival and is linked to famine (FAO, 2013). While being widely accepted and regarded as a delicacy in other regions of the world. The readily available edible insects can be purchased at neighborhood food shops and consumed in daily life. The transition to a western diet has threatened entomophagy in these nations where edible insects are a part of the diet. This scenario might be avoided if the western perceptions towards edible insects' changes. The prevalent views across many regions of the world were discussed in

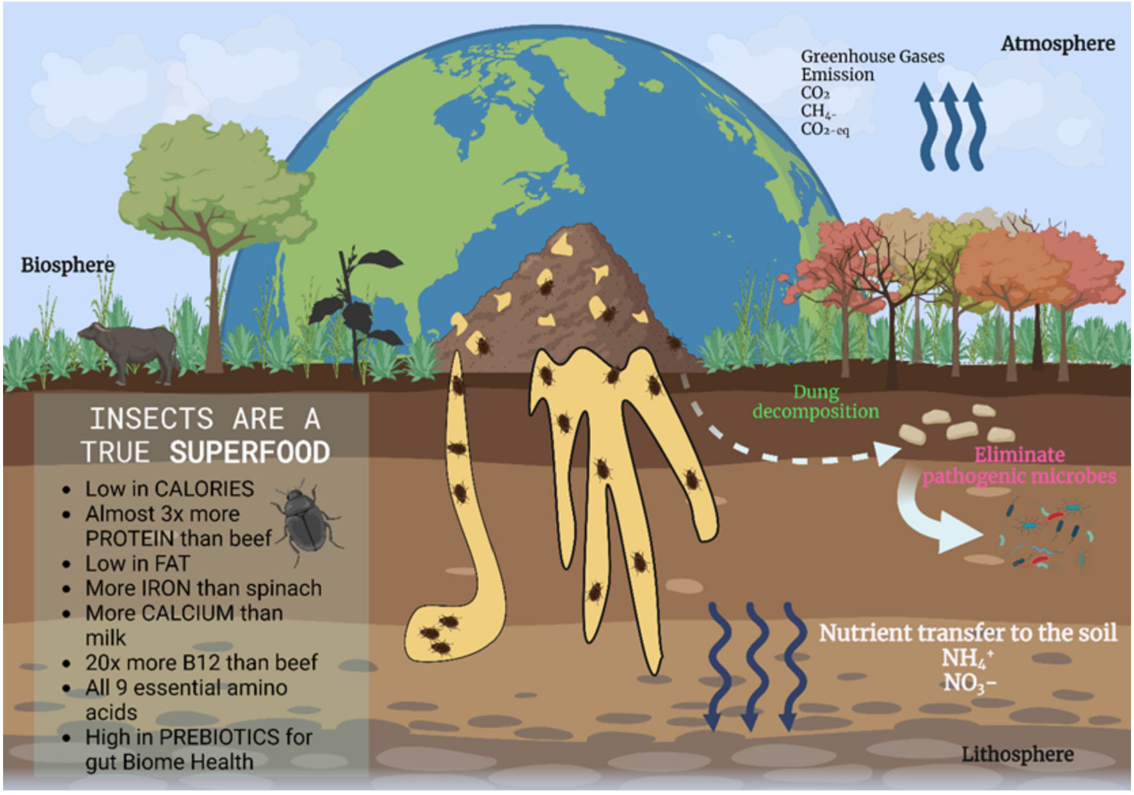

FIGURE 11 Environmental benefits of Coleoptera consumption.

these sections, along with the role of cultural factors in Coleoptera consumption.

10.1 *Attitudes in different regions of the world*

Several challenges associated with edible insects including Coleoptera as an insect-based food or alternative protein source are particularly based on consumer acceptance and commercialization. Highland Quechua people consume Coleoptera on occasion, and it is well-accepted by the local community. These foods are conserved by Amazonian Amerindians primarily as an alternative for food scarcity during the rainy season, as well as an accessible forest resource and year-round agricultural by-product (Manno *et al.*, 2018). Whereas, in New Zealand, more than 60% of participants claimed they would consume insects frequently if they were in a suitable kind, such as a capsule, which is for better wellness (Payne *et al.*, 2023). The participants demonstrated knowledge of the favorable ecological effects associated with the consumption of insects as a protein source compared to other alternatives. However, their awareness regarding the potential health benefits of consuming insects was comparatively lower. Individuals in New Zealand and Australia can legally consume other insects, including beetles, grasshoppers, butterflies, moths, bees, bugs, and dragonflies nevertheless they are not allowed to be sold. Any meals containing insects must be identified, and if an insect is 'novel,' it must undergo a risk-assessment procedure that takes toxicology, nutrition, and consumption patterns into account (Lähteenmäki-Uutela *et al.*, 2021; Payne *et al.*, 2023).

Alhujaili *et al.* (2023) presented a comprehensive framework that encompasses factors from many geographies, which have an impact on consumers' willingness to accept insects as a food source. Several characteristics, including unpleasantness, food neophobia, familiarity, sight of insects, and taste, have been identified as significant elements that may contribute to consumers' reluctance to accept insects as a food source (Alhujaili *et al.*, 2023). Meanwhile according to earlier studies, older people in China and Japan were noticeably more likely than younger people to consume insects because they had more past experience doing so. This highlights the importance of centuries-old traditions (Liu *et al.*, 2019; Payne, 2015). In addition to this, apprehensions pertaining to the ramifications of food consumption on an individual's overall health and the environment could also impact the level of acceptance. For example, individuals who express concerns regarding the environmental and health implications associated with insect consumption have a higher inclination, around 22% more, towards engaging in the consumption of insects, in comparison to individuals who do not share such concerns (Palmieri *et al.*, 2019).

The phenomenon of food neophobia exerts a detrimental influence on the general populace's inclination to embrace insects as a viable food source, in both industrialized and emerging nations, such as Italy (Laureati *et al.*, 2016; Barbera *et al.*, 2018; Sogari *et al.*, 2019; Palmieri *et al.*, 2019; Menozzi *et al.*, 2019; Tuccillo *et al.*, 2020), Germany (Dupont and Fiebelkorn, 2020; Lammers *et al.*, 2019; Orsi *et al.*, 2019; Ruby and Rozin, 2019; Schäufele *et al.*, 2019), Norway (Orkusz *et al.*, 2020), Switzerland (Schlup and Brunner, 2018), Australia (Bogueva *et al.*, 2019), Hungary (Gere *et al.*, 2017), Taiwan (Chang *et al.*, 2019), China (Liu *et al.*, 2019), and Uganda (Olum *et al.*, 2021). Furthermore, the insect species employed in the insect-based product can have an impact on the taste, impacting its acceptance (van Huis, 2020). Tuccillo *et al.* (2020) discovered that the most desired insects in Italy besides Coleoptera were crickets, bee larvae, grasshoppers, silkworms, and gigantic water bugs. The researchers also examined the impact of insect life cycle stage on consumer acceptance of insect-derived snacks and found that adult insects were perceived as more favourable compared to their larval counterparts. In Romania, consumers who exhibited a willingness to consume insects demonstrated a preference for locusts and ants over several other species-specific food items, such as crickets and worms (Simion *et al.*, 2019).

Few studies concerning substantial aspects of household income and size. In China and Poland, there exists a positive correlation between higher-income households and their propensity to embrace insects as a dietary source (Liu *et al.*, 2019; Orkusz *et al.*, 2020). In China, larger households made insects more edible (Liu *et al.*, 2019), whereas in Kenya, larger household sizes lowered acceptability (Pambo *et al.*, 2018). Tan *et al.* (2016) demonstrated in the Netherlands that Coleoptera product adoption may depend on consumer perceptions of insect-based food transporters. According to the research, Dutch participants thought meatballs were suitable and dairy drinks were unsuitable. As a result, makers of insect-based products should keep this in mind when selecting food carriers, as different carriers evoked varying levels of readiness to pay.

Ardoin and Prinyawiwatkul (2020) reported that protein bars, chips, snack crackers, and protein beverages were the most acceptable among 30 items, including hamburgers, crab cakes, and cheese, for US participants (Ardoin and Prinyawiwatkul, 2020). Poortvliet *et al.* (2019) revealed that due to its perceived unhealthiness and nastiness, diners were less likely to try an insect-based burger (Poortvliet *et al.*, 2019).

10.2 *Role of cultural factors in Coleoptera consumption*

Culture has profound effects on people's food preferences as well as their eating-related attitudes and beliefs (Enriquez and Archila-Godinez, 2022). The cultural background of consumers affects how they view food, which influences how much they would utilize and accept the food (Laaksonen *et al.*, 2020). Prior study has concentrated on the impact of customers' cultural backgrounds on sensory perception and acceptance when evaluating food samples. The study looked at the effects of cultural differences in familiarity and anticipation, as well as the influence of social values and beliefs on consumer reactions to foods. As an alternative protein source, insect-based meals are popular due to their excellent nutritional content and inexpensive manufacturing costs (Simeone and Scarpato, 2021).

In recent years, there has been a significant amount of interest directed on meals centered around insects as a viable alternative source of protein, mostly because of their cost-effective production methods and rich nutrient composition. Neophobia, also referred to as the aversion and avoidance of novel or unexpected dietary items, (Barrena and Sánchez, 2013), is one of the contributing factors to the elevated rate of market failure in the food sector pertains to innovations, and distaste has a far higher explanatory power (La Barbera *et al.*, 2018). The acceptance of cultured meat and insect-based cuisine among German children and teens was explored in the study by Dupont and Fiebelkorn (Dupont and Fiebelkorn, 2020). The findings indicated that the respondents preferred eating the cultured beef burger over the bug burger. The respondents did, however, consider cultured meat and meals based on insects to be quite comparable. When doing individual assessments, insects as a food source garnered superior scores in terms of both disgust and ethics compared to bug burgers. However, insects also obtained greater ratings in relation to health and environmental considerations. Thus, in many countries, it is still quite difficult to get people to eat dishes made from insects. In diverse cultures, acceptance or rejection of insects is mostly influenced by traditions, superstitions, and taboos. Other deciding elements include the kind of edible insects that are available close by, as well as their appearance and taste (Dupont and Fiebelkorn, 2020).

Additionally, motivation based on curiosity, or a dietary requirement may predominate (Ghosh *et al.*, 2018). Consumer approval of insect-based food as a source of nutrition was the subject of consumer opinion. According to Kostecka *et al.* (2017), interest in insect-based foods is still low in European nations, and Western nations' dietary preferences are largely influenced by individual opinion (Kostecka *et al.*, 2017). Consequently, the introduction of insects into Western cuisine will include a transitional period that sees the addition of powdered insects to ready-to-eat dishes because people aren't yet prepared to consume whole insects (Megido *et al.*, 2016). Vegetarian and insect food consumers are viewed as being more educated, intriguing, and environmentally conscious than meat eaters, and they may have a good societal impact (Hartmann *et al.*, 2018). The propensity of individuals to consume meals derived from insects may exhibit a correlation with their social companions and the specific setting in which the consumption occurs, which is linked to pleasurable and stimulating sensations rather than good and soothing emotions. These findings provide potential avenues for augmenting consumer receptiveness towards insect-based food products (Motoki *et al.*, 2020). According to previously published studies, it can be concluded that the strategy ought to address the positive aspects of eating insects due to their nutritional qualities and environmental advantages over current meat products. This has the effect of increasing consciousness and interest among consumers in the use of sustainable proteins. Nevertheless, corporations should focus on market expansion and the drivers that appeal to the most sophisticated and aware consumers. Since these consumers are typically well-informed about new product features and food trends, they may be more likely to try new items. Besides, the possibility of allergies for consumers who are less knowledgeable and who may be interested in eating insects should be considered.

11 Harvesting and rearing of edible Coleoptera

The species of edible insects, local practices, and the time of year all influence the methods of harvesting, processing, and preservation. This strategy represents a viable approach to generating protein-rich food and feed while minimizing the environmental impact. Common techniques for catching insects in entomology were employed throughout the collection of materials. In Lithuania, Lekoveckaitė *et al.* (2023) used modified emergence type traps to present the results of the first comprehensive research of saproxylic beetles. To preserve the environmental conditions inside the trap, translucent, air-permeable polyester material was used to sew the traps. To promote the upward flight of insects exiting from the wood, each trap is designed with one vertical wall that is taller than the other. Every trap was specifically designed to encompass a segment of the wind-felled tree measuring one meter in length. Each trap's bottom was sealed by affixing contact tape to the cloth. The trunk needs to be lifted off the ground to properly install the traps. To prevent the fabric from developing wrinkles, traps were set in the central sections of these trunks, stretching their walls with the aid of woven ropes. From June through October, every two weeks, a two-piece collecting jar that was filled with >99% propylene glycol and affixed to the trap's highest point was emptied. 82 samples in total were collected over the course of the four-year study (Lekoveckaitė *et al.*, 2023).

Saproxylic beetles are collected using a variety of techniques (Cheong, 2019; Micó *et al.*, 2020; Parisi *et al.*, 2020), the most common of which include window traps, trunk window traps, and emergence or elector traps. In Germany (Müller *et al.*, 2015), France (Bouget *et al.*, 2012), Italy (Parisi *et al.*, 2021), and Sweden (Henneberg *et al.*, 2021; Hjältén *et al.*, 2010), closed emergence traps have been used to gather beetles in a similar way. For instance, compared to their study, the number of beetle species collected in Germany (381 species) was lower despite having collected data from half as many tree species and much more trunks than they did (Müller *et al.*, 2015). Beetles were also manually collected from their hiding places and the soil's surface, by entomological filtering, and at night from an artificial light source. In addition, beetles were captured using pitfall traps (Baulechner *et al.*, 2019; Naccarato *et al.*, 2020).

One can examine ground beetle (carabid) assemblages in several ways. Among these include litter cleaning, handpicking, pitfall traps, window traps, malaise traps, sweep netting, and sticky traps (Nasir *et al.*, 2019). These pitfall traps are the most popular field technique since they can quickly and cheaply capture ground beetles. Pitfall trapping, however, has a variety of disadvantages. Catch rates from pitfall traps depend on the species' activity, which differs depending on the species and the season. Pitfall catches therefore accurately represent the species' actual activity and abundance. Pitfall traps capture larger animals than other techniques, such as litter washing, but hand collecting frequently produces species that are not caught in pitfall traps (Gobbi *et al.*, 2018; Jung *et al.*, 2019; Knapp *et al.*, 2020). It is straightforward to modify pitfall traps to meet the criteria of the investigation. The environmental conditions and purpose of the survey, as well as the types of plants where the collection is taking place, define the appropriate collecting strategy (Gardarin and Valantin-Morison, 2021). 1/3 of a 0.5 L plastic glass that contains 4% formalin. Ten soil traps were set up between late May and mid-October, each 10 meters away from the agricultural area being researched. Every 7 to 10 days, insects are removed from the trap. Microscopy was used to identify the laboratory-collected samples of the study.

The usage of specialist procedures increases as data collection experience or the target group narrows. Despite the ease and occasional effectiveness of picking beetles by hand, previous studies describe how several types of equipment and unique methods are typically required due to the beetles' size, mobility, and risk of being bitten or stung (Kumar *et al.*, 2022; Schauff, 2001). Frequently, a gathering net and several killing bottles will do. A certain fauna can be sampled more thoroughly with the addition of more objects, though. A lot of collectors carry a bag or wear a vest where they keep their gear. The development of the rearing method opens the prospect of employing molecular methods to investigate these alterations in addition to providing a complete system for examining the biology of the beetle. The air potato beetle, *Lilioceris cheni Gressitt* and *Kimoto* (Coleoptera: Chrysomelidae), was mass-reared according to Kraus *et al.*'s (2022), which details its production, dissemination, and developments (Kraus *et al.*, 2022). Adults who consume fresh air potato leaves succeed most. They may do well on a specially formulated diet for weeks and then go starved for several days to several weeks, based on what they consumed before. This makes less leaf tissue, which is needed for populations to survive the winter. Artificial diets are insufficient for larvae to continuously survive. This finding demonstrates that mature beetles possess the ability to endure periods of famine during their dispersal or shortly after being released. This adaptive trait enables mass-rearing programs to effectively control tissue growth in beetles at specific stages of their annual cycle. Additionally, this suggests that a consistent supply of fresh-air potatoes vines is necessary throughout the entire year, preferably in substantial quantities.

In meanwhile, Riddick *et al.* (2019) showed that it is possible to increase the reproductive potential of mass-produced Ladybird beetles by using cheap, easily accessible bioflavonoids and their breakdown products. Their study's results show that 2,4-dihydroxybenzoic acid (DHBA), an efficient chemical stimulant, may cause some *C. macuata* females to oviposit in cages in particular places, such as DHBA-containing Petri dishes (Riddick *et al.*, 2019). This study implies that before stimulation takes place, females must physically interact with and maybe consume DHBA. Feminine grouping into communal cages would be a space-saving method for effective mass rearing. When there was no tissue substrate present elsewhere in the communal cage experiment, most egg clutches were found in or close to the chemical dish containing DHBA, indicating that DHBA may have served as an oviposition stimulant in part. However, more research is needed to fully understand the physiological process underlying oviposition stimulation. In some mass-rearing methods, DHBA may act as a weak oviposition stimulant for predatory ladybird beetles.

Hasan and Phillips (2010) have described a novel mass-rearing method for the red legged ham beetle, *Necrobia rufipes De Geer* (Coleoptera: Cleridae), which makes it possible to produce lots of beetles with little handling work (Hasan and Phillips, 2010). On *N. rufipes*, a culture medium made up of pieces of dried cured ham, dry dog chow, and Dried fish that has been finely pulverized (150 μm) was examined. When considering a range of public and unpublished approaches, this way of rearing yielded noticeably higher population numbers. Over the course of 7-8 weeks, *N. rufipes* adult populations increased by more than three times raised on this setting with 200 mixed-sex mature beetles at the start. By moving the larvae into glass vials to produce pupal cells, this straightforward approach reduces cannibalism.

Additionally, recent research has shown that it is simple to mass rear the mealybug predator *C. montrouzieri Mulsant* (Coleoptera: Coccinellidae) on several types of mealybugs (Gunawardana and Hemachandra, 2020). *P. viburni* and *P. minor* were grown on pumpkins. Utilizing indigenous pumpkins, *Cucurbita moschata*, increased production of *C. montrouzieri* substantially. The local pumpkin variety *C. moschata* (surface area 1000 cm^2) might be used to produce an average of 300.3 ± 41.8 yield of *C. montrouzieri* adults. The cost of production for a single predatory beetle, *C. montrouzieri*, was determined to be lowest (Rs. 24.11), with mealybug species, *P. minor*, raised on local pumpkin. Figures 12 and 13 depicts the chronological steps in the mass rearing of *C. montrouzieri* on pumpkin. Prior research has indicated that numerous variables exert an influence on the efficacy of mass-rearing, with special emphasis on the dietary component provided to the insect (Broekhoven

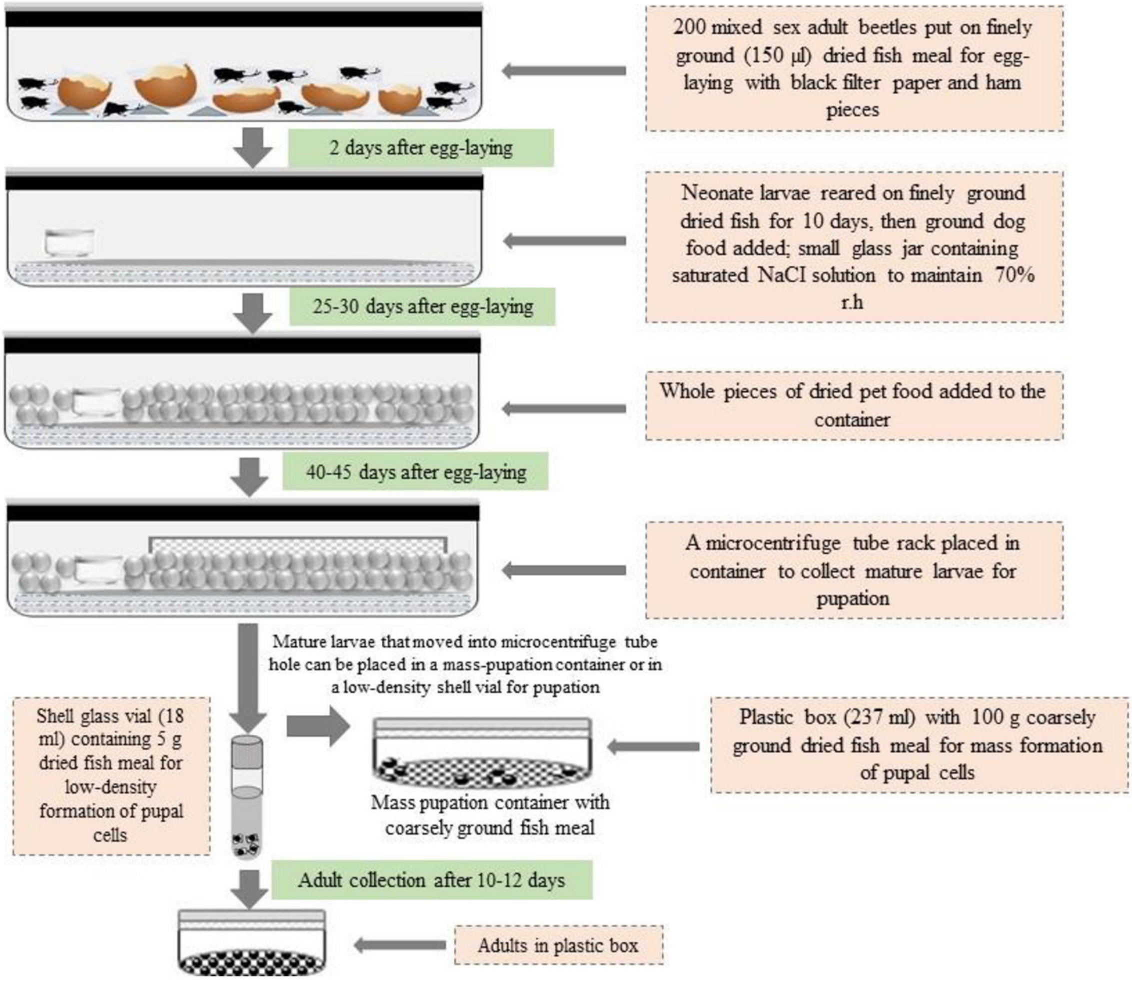

FIGURE 12 Captive breeding of the red-legged ham beetle, *Necrobia rufipes De Geer*, on a large scale. Hassan and Philips, 2010.

et al., 2015). The development of mealworms and their feed conversion efficiency were found to be influenced by diet composition. Diets rich in protein generated from yeast were shown to be more advantageous compared to the diets commonly employed by commercial breeders. These yeast-based diets were seen to result in shorter time for larvae to grow, lower death rates, and more weight gain in mealworms. The chemical makeup of mealworms was similarly influenced by their diet. The larvae's fat level and fatty acid makeup were changed by the fat they consumed. Nevertheless, the lipid composition of the larvae's fats did not consistently align with the content of their feed in terms of fatty acids. Besides that, limited study investigations have been conducted pertaining to the rearing settings and the impact of various substrates on the growth and chemical-biological attributes of mealworm larvae. The majority of the referenced research has emphasized the adaptability of *T. molitor* in response to different substrates, resulting in changes in both larval development durations and nutritional content (Broekhoven *et al*., 2015; Dreassi *et al*., 2017; Fasel *et al*., 2017). Nevertheless, the researchers included various combinations of substances as substrates in their investigations, as their primary objective was to ascertain the impacts of different proportions of proteins, lipids, and carbs. Apart from that, temperature is a fundamental abiotic element that influences the growth and productivity of insects. Bjørge *et al*. (2018) conducted a study to examine the impact of rearing temperature on the developmental rate and performance, along with nutritional composition of two species of edible beetle larvae, namely *Alphitobius diaperinus* and *T. molitor* (Bjørge *et al*., 2018). The study demonstrated that *A. diaperinus* exhibited reduced growth rates at lower temperatures and increased growth rates at higher temperatures in comparison to *T. molitor*. However, both species showed an optimal growth rate at a temperature proximate to 31 °C. The growth rates observed at the optimal conditions in this study exhibited a significant level of magnitude, indicating a substantial potential for mealworms as viable candidates for animal production purposes.

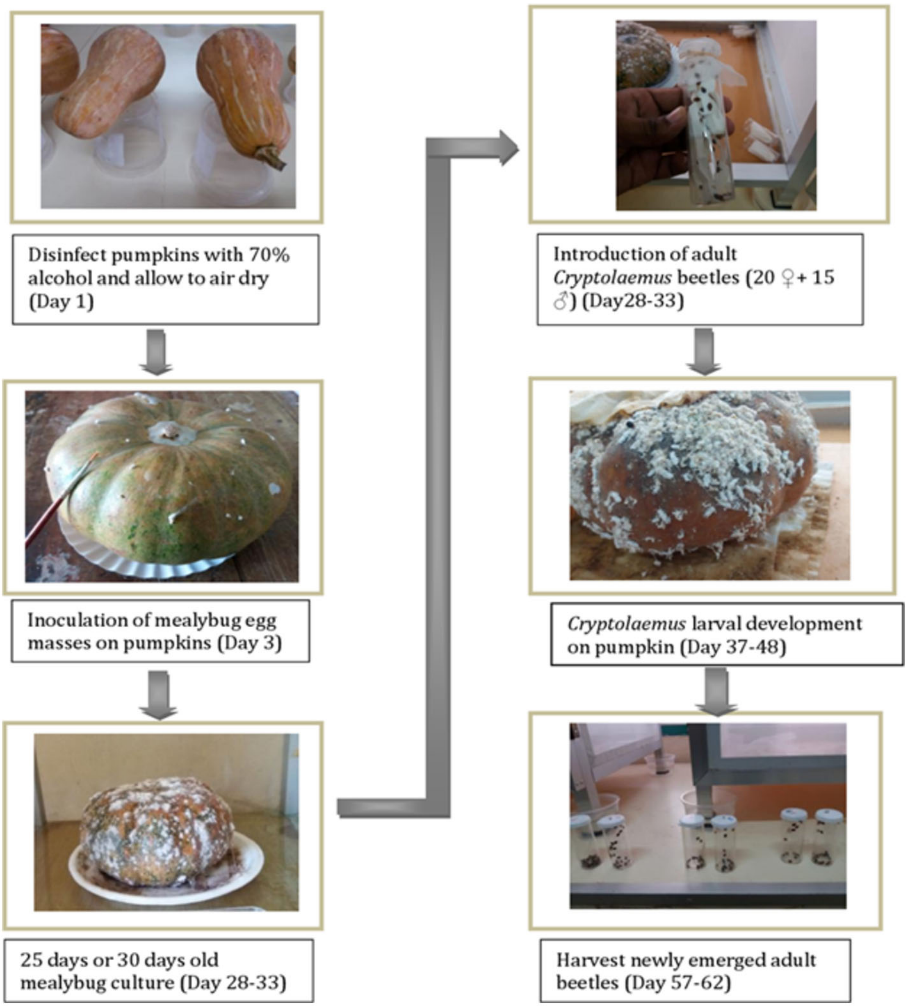

FIGURE 13 Chronological steps in the mass rearing of *C. montrouzieri* on pumpkin. The image obtained from Gunawardana and Hemachandra, 2020. Copyright 2020 by Tropical Agricultural Research under Creative Commons Attribution 4.0 license. Reprinted with permission.

However, in another study, it has been observed that increased temperatures may have a detrimental impact on the physical dimensions of beetles. In a study conducted by Macagno *et al.* (2018), it was shown that *Onthophagus taurus* (Schreber, 1759) specimens exhibited reduced size when exposed to higher temperatures (32 °C) in comparison to lower temperatures (24 °C) (Macagno *et al.*, 2018). The observed phenomenon of diminished growth led to a decrease in both the size and survival rate of progeny in succeeding generations.

Apart from that, there was a notable distinction between the two species in terms of growth. *T. molitor* exhibited a larger accumulation of lipid compared to *A. diaperinus*. Conversely, *A. diaperinus* displayed a faster rate of protein accumulation than *T. molitor* under optimal temperature conditions. The energy content of the two species, *T. molitor* and *A. diaperinus*, was typically equivalent at the completion of the growth experiment, despite the fact that the juvenile *T. molitor* larvae contained fewer lipids than juvenile *A. diaperinus* (Bjørge *et al.*, 2018). In summary, the effectiveness of a rearing program hinges upon the thorough understanding and provision of the target species' nesting and habitat requirements, as well as its abiotic need. Once a rearing system has been established, it serves as a valuable resource for the mass expanding of candidate species or as a controlled platform for conducting research. This allows for the acquisition of novel insights into the biology of the target dung beetle, which may not have been attainable through field investigations alone. The effectiveness of mass-rearing across different species can be affected by a number of factors, some of which are summarized in Supplementary Table S3.

12 Processing and packaging of edible Coleoptera as human food

Insect processing is essential for producing safe and superior raw materials, components, and finished goods that are appropriate for use on a wide scale in the food and feed sectors. There has been a notable increase in the food industry's attention towards this innovative protein source, as indicated by the emergence of numerous startup companies and a significant number of scientific publications over the past decade. Market analysis suggests that there is a growing global demand for edible insects, with projections estimating a market value of approximately US $8 billion within the next decade (Liceaga, 2022). Due to the growing market demand in Western cultures, alternative methods for preparing insects have emerged. These methods involve various processing techniques that transform insects into forms that are no longer recognizable, such as flours, powders, protein hydrolysates, and fermentable substrates (Melgar-Lalanne *et al.*, 2019; Liceaga, 2022). The processing routes employed in food and feed processing are contingent upon the characteristics of the starting material and the intended final result. These pathways may encompass many unit activities that are now utilized in the field. The many steps of insect processing include harvesting, preliminary processing, decontamination, follow-up processing, packaging, and storage. For the treatment of edible insects, a variety of conventional and industrial decontamination procedures have been proposed. These techniques include toasting, drying, blanching/boiling, frying, marinating, and smoking, as well as various combinations thereof. According to the study conducted by Ojha *et al.* (2021a), additional processing techniques are utilized in order to generate insect meal and flour, and the removed portions derived from insects (Ojha *et al.*, 2021b). The microbiological and chemical characteristics of finished material will be affected differently by each treatment. new techniques for preparing food, such as cold plasma, ultrasonic, pulsed electric field, and high pressure have demonstrated promise in altering, supplementing, or substituting the traditional processing methods employed in insect processing. The aforementioned methods have undergone testing to assess their efficacy in microbial cleansing, enzyme inactivation, extraction and drying (Ojha *et al.*, 2021a). Moreover, these technologies are widely recognized for their environmentally sustainable attributes and can be effectively utilized across several domains to enhance the operational effectiveness, safety, and overall excellence of insect-derived commodities.

The optimal organization of each processing route entails three sequential steps: (1) pre-processing, (2) sanitization, and (3) wrapping with stowing. Numerous cleansing techniques are being suggested for the treatment of edible insects. Numerous combinations of blanching, cooking/boiling, steaming, marinating, drying, smoking, and toasting are included in this category. The various operations will exert distinct effects on microbiological and chemical characteristics of ultimate material. The efficacy of processing technology is contingent upon various factors, including the specific insect species being processed, potential safety issues associated with the process, and the intended nature of the final product. The primary aim of food processing is to guarantee the safety of food products. Nevertheless, it is equally crucial to meet established quality criteria and fulfill consumer demands. In the present setting, it is crucial to consider microbiological safety. Several nations throughout Europe, including Belgium and the Netherlands have established microbiological limitations for the consumption of edible insects (EFSA Scientific Committee, 2015).

Pre-processing technologies are an integral initial stage in the processing of edible insects. These technologies primarily involve the separation and harvesting of insects from substrate residuals, the inactivation or death of insects, the elimination of legs, wings, and washing process (Rumpold and Schlüter 2013b). Upon reaching proper size or a specific age, the insects are collected using either human or automated means. Larvae (mealworms, and smaller mealworms) are typically isolated through the process of sieving. According to the findings of Wynants *et al.* (2017), the overall viable counts of yellow mealworms did not decrease as a result of the starvation procedure or induce consistent changes in the makeup of the bacterial community.

After the process of harvesting, the insects are subjected to several postharvest treatments before their consumption. The initial action involves the termination of the insects unless they are being marketed as live specimens. Freezing and immersion in warm or steaming water are among the prevailing techniques frequently employed for this objective. According to Adámková *et al.* (2017), mealworms subjected to direct immersion in boiling water had a decreased fat content in comparison to those subjected to freezing.

To mitigate the microbial burden, it is possible to integrate a rinse or washing step with the killing process, a practice already employed in conventional food items such uncooked vegetables and fruits (Yoon and Lee, 2018) as well as animal corpses and meat (Huffman, 2002). Nevertheless, the studies done by Ng'ang'a *et al.* (2020) and Wynants *et al.* (2016, 2017) pertaining to mealworm larvae demonstrated that the application of a 1-minute cleaning procedure using sterilized or tap water did not result in a decrease in total viable count (TVC), bacterial endospores and molds, yeast, Enterobacteriaceae, mesophilic aerobic count. Crippen and Sheffield (2006) reported that superior outcomes have been achieved in smaller-sized mealworms when utilizing germ-free water supplemented with agents: e.g. H_2O_2, ethanol, and NaClO. While the aforementioned washing tests were conducted on living larvae, it is worth noting this model may also be applicable to deceased insects. Another study by Klunder *et al.* (2012) exhibited significant reductions in the levels of TVC, Enterobacteriaceae, and bacterial endospores on *T. molitor* following boiling or roasting in water for a duration of 10 minutes. Specifically, the reduction levels observed were as follows: TVC decreased from 7.5 to less than 1.7 log cfu/g, Enterobacteriaceae decreased from 6.8 to less than 1 log cfu/g, and bacterial endospores decreased to 1 from 2.1 log cfu/g (Klunder *et al.*, 2012).

Blanching is a widely employed procedure within the food business. The process of blanching facilitates the deactivation of vegetative germs, whereas bacterial spores remain unaffected. The term "blanching" denotes a culinary technique involving the immersion of food in boiling water for a brief period, typically ranging from a few seconds to over ten minutes, depending on the specific product, and subsequently, the meal is rapidly chilled in water (Xiao *et al.*, 2014). Vandeweyer *et al.* (2017b) conducted an experiment to examine the impact of blanching durations of 10, 20, or 40 seconds, whether microwave drying is used or not, on *T. molitor* larvae, which are edible insects. A noteworthy decrease from 8-1.3 log cfu/g in the overall aerobic amount was found by subjecting the sample to a blanching duration of 40 seconds after microwave treatment lasting a minimum of 16 minutes, resulting in a residual moisture content of 0.6%. The microbial reductions observed were comparatively lower in instances when no microwave procedure was used, or when shorter microwave treatment times were used after blanching (Vandeweyer *et al.*, 2017b). In addition, the researchers demonstrated that the process of blanching shown efficacy in reducing the population of fungi and Enterobacteriaceae, specifically molds, to levels that were undetectable using the designated detection criteria of 2 log cfu/g for fungi and 1 log cfu/g for Enterobacteriaceae. However, it should be noted that a rise in bacterial endospores was detected as a result of this blanching process (Vandeweyer *et al.*, 2017b).

To increase the shelf life of food goods, drying is a common technique used in the food industry. Drying techniques encompass a spectrum of approaches, including both conventional methods, e.g. frying, roasting and sun-drying, besides contemporary technologies like freeze-drying and microwave-assisted drying (Melgar-Lalanne *et al.*, 2019). The process of drying has the potential to decrease the overall water content, reducing its obtainability for degradative processes with enzymatic and reactions brought on by spoilage microorganisms. Microorganisms are multiplying and are influenced by the level of water activity (aw). The growth of the bulk of bacteria ceases when the water activity (aw) falls below 0.65. When the availability of water is limited, microorganisms exhibit a deceleration in their development rate. Conversely, under favorable water circumstances, they are capable of resuming their growth (Grabowski and Klein, 2017b,c). Tenebrio molitor can be subjected to several drying procedures including oven drying, microwave-assisted drying, freeze drying, fluidized bed, hot air and vacuum drying (Hernández-Álvarez *et al.*, 2021; Ojha *et al.*, 2021a). The process of hot air drying is generally employed in the food sector. In this particular drying process, the transfer of heat occurs through convection, wherein the hot air conveys thermal energy to the product. Simultaneously, the water undergoing evaporation is moved to the surrounding air (Torki-Harchegani *et al.*, 2016). Various research employs diverse techniques for conducting hot drying in the preparation of mealworms. According to a study conducted by Kröncke (2018), conventional hot air drying was performed using an oven. In the experimental setup, a backing plate with dimensions of 60 × 80 × 2 cm was utilized. A total mass of 800 g of larvae was evenly distributed as a thin layer on the surface of the backing plate. This arrangement was positioned at the center of a rotating convection oven. Apart from that, frozen larvae underwent a drying process for a duration of 1 hour at a temperature of 120 °C during ventilation stage 2. The findings of this experiment revealed a considerable decrease in both water activity and moisture content (Kröncke *et al.*, 2018).

The utilization of microwave technology for the purpose of drying is gaining popularity as a result of its ability to heat materials uniformly throughout their volume and its capacity to significantly decrease drying durations (Kumar and Karim, 2019).The utilization of Microwave-assisted drying, in conjunction with a 40-

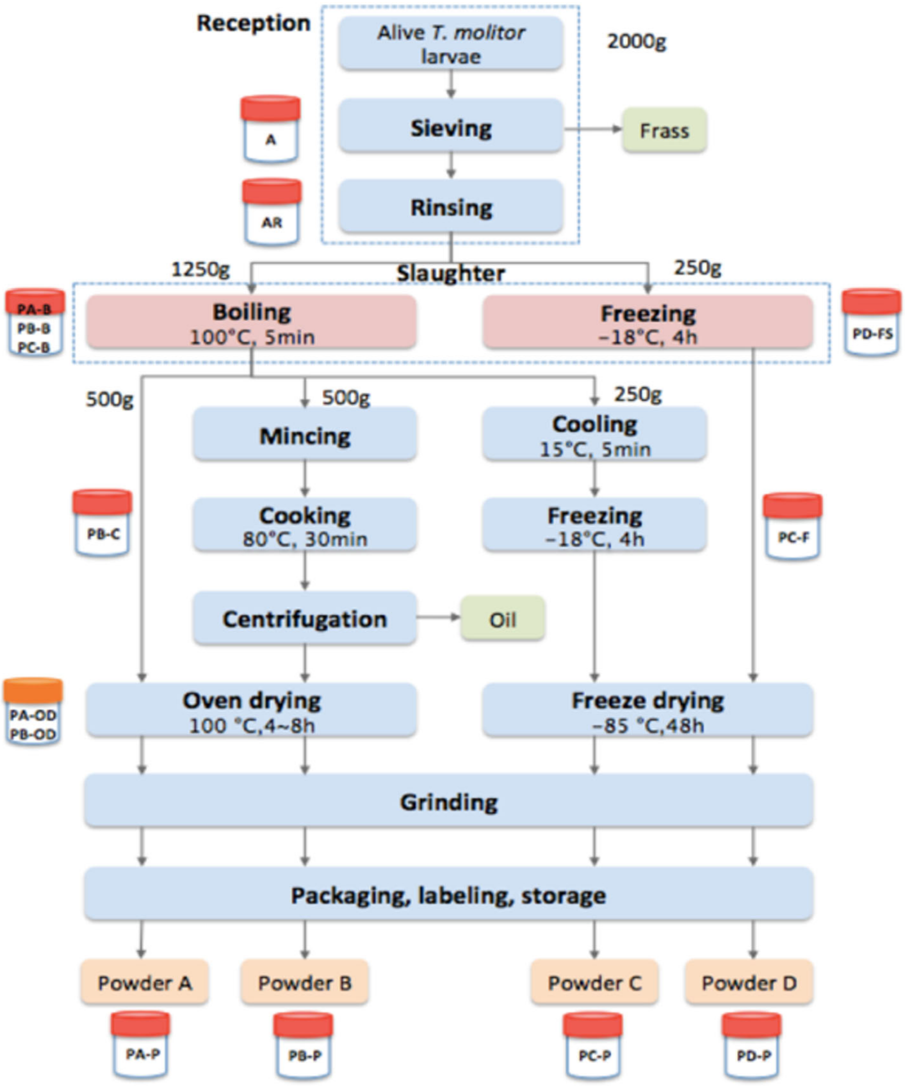

FIGURE 14 A diagram illustrating the various routes involved in the processing of mealworm powder and the subsequent collecting of samples. Adaptation from Kooh *et al.*, 2020.

second blanching process lasting shorter than 16 minutes, was shown to be ineffective in achieving a water activity level below 0.6 (Vandeweyer *et al.*, 2017b). Furthermore, it has been observed that elevated drying temperatures lead to the occurrence of darkening and shrinkage in *T. molitor*, which can be ascribed to tissue damage and browning reactions (Purschke *et al.*, 2018).

Freeze-drying is often regarded as a highly effective drying technique for the preservation of premium-grade materials. The process described is predicated upon the dehydration of a frozen product through sublimation (Ratti, 2013). According to Stapley (2009), the product often exhibits a high level of quality as a result of the utilization of low processing temperatures and the elimination of oxygen (Stapley and Rielly, 2009).The freeze-dried mealworm larvae, whether blanched or not, have a significantly low water activity level, measuring below 0.30. The observed decrease in aw is expected to have a concomitant effect on enzymatic activity. Non-enzymatic browning processes may transpire, albeit at a significantly sluggish pace, owing to the prerequisite of a minimum water activity of 0.20 for such reactions to take place. Hence, freeze-drying presents a feasible and commercially significant method for the processing of insect biomass of superior quality suitable for consumption. Figure 14 depicted the mealworm powder processing pathways and collection of samples.

The findings of Lenaerts *et al.* (2018) indicated that there were no statistically significant proximate protein content differences between mealworms that have been dried using a microwave and those that have been frozen, regardless of whether a blanching step was performed prior to drying (Lenaerts *et al.*, 2018). Nevertheless, it has been found that samples that have been freeze-dried have statistically significant higher quantities of unsaturated fatty acids than samples that have been dried using alternative procedures (Selaledi and Mabelebele, 2021). In contrast, the analysis revealed that microwave-dried mealworms exhibited a statistically significant decrease in monounsaturated fatty acids and a corresponding increase in polyunsaturated fatty acids when compared to freeze-dried mealworms. This disparity renders microwave-dried mealworms more prone to oxidation. In freeze-dried mealworms, the amount of polyunsaturated fatty acids was lower than expected, and it could b be due to an elevated level of lipid oxidation (Kröncke *et al.*, 2019). Furthermore, the application of blanching in conjunction with freeze drying resulted in alterations to the fatty acid composition as compared to fatty acid profile of only freeze-dried mealworms. A disparity observed in levels of saturated fatty acids between freeze-dried and blanched mealworms (Ravi *et al.*, 2021). The main cause of the observed discrepancy is the presence of less myristic, palmitic, and stearic acid. On the other hand, using blanching in addition to microwave-assisted drying had minimal impact on the fatty acid composition in comparison to microwave assisted drying as a standalone method. The investigation focused on examining the impact of different drying techniques on both the fatty acid and fat particles size. Previous studies have shown that thermally dried samples have an upward tendency in fat content as particle size increases, whereas freeze drying results in the opposite trend, with higher fat concentrations observed in the finer particle fractions. The impact of various processing techniques on nutritional composition and lifespan of edible Coleoptera is demonstrated in Table 11.

Historically, edible insects have been commonly available in dried and/or crushed forms, often advertised as heat-dried larvae, flour, pupae, and intact insects. A diverse range of edible insects can be found in the market, offered in various formats such as canned, powdered or flour foodstuffs, nibbles, chocolates and even liquor infusions. According to the study conducted by Melgar-Lalanne *et al.* (2019), in the past decade, a number of enterprises and emerging ventures have emerged globally, with a primary focus on Europe, South Asia, and North America. These entities have established with the objective of commercializing food products derived from insects, intended for human use (Melgar-Lalanne *et al.*, 2019).

The storage conditions are contingent upon the specific insect species and the form in which the product is marketed, either as whole and ready-to-eat insects or as powder obtained through drying procedure. Every product category has a distinct shelf-life form, which is determined by the cumulative sum of the initial counts of the raw product, along with adjustments resulting from processing and secondary contamination. In addition, the optimal method for long-term storage of yellow mealworm (*T. molitor*) and lesser mealworm (*Alphitobius diaperinus*) involved the use of boiling water for killing, followed by drying at a temperature of 103 °C for a duration of 12 hours. Subsequently, the insects were packaged in a hermetic manner (Adámek *et al.*, 2019). In order to retain the microbiological quality of *Zophobas atratus*, it is recommended to store them at a temperature of −20 °C through freezing, rather than refrigeration at 5 to 7 °C. Furthermore, cooling is the most effective approach for preventing oxidative and microbiological deterioration of dried and powdered superworms (*Zophobas atratus*) (Grabowski and Klein, 2017b).

T. molitor and *Alphitobuous diaperinus* larvae were used to make minced meat-like items, which were refrigerated for storage using a modified environment composition of 60% CO_2 and 40% N_2. A notable decrease in microbial proliferation was reported in comparison to samples maintained under standard air conditions. The aerobic count of *T. molitor* exhibited a low level (1.0 log cfu/g) after a 28-day storage period under a modified environment. In contrast, samples held under ambient conditions showed a higher total aerobic count of 6.9 log cfu/g. In contrast, *A. diaperinus* exhibited a limited storage capacity of just 14 days when subjected to modified atmospheric conditions, resulting in a bacterial count of 1.9 log CFU/g. The bacterial community composition exhibited variations between the two stored products, with a notable decrease compared to the bacterial composition observed in raw minced meat obtained from conventional bases. The shelf life of the product is also contingent upon the specific minced species utilized. Prior to keeping this kind of product in altered environments, it is imperative to do an analysis of the particular presence of food pathogens (Flekna *et al.*, 2017; Stoops *et al.*, 2017).

The process of sealing and packing insects is a crucial component of the manufacturing process, as it significantly impacts the quality of the items upon reaching the end-user. In order to ensure the delivery of safe food or feed, it is imperative to adhere to proper hygiene, environmental, security, and quality policies throughout the packing process. In order to achieve this objective, a number of measures are suggested. The company employs packing methods to assure its cleanliness prior to the introduction of insects. Disinfection should be carried out as deemed necessary. The producer ensures that the packaging is promptly sealed following the filling process. In order to prevent the proliferation of unwanted pests, it is imperative to maintain cleanliness in storage rooms and containers. The monitoring and maintenance of humidity and lighting levels are conducted in accordance with the specific requirements of the end-product.

When conducting the sealing process for the final product, the operator takes measures to verify that the sealed bag does not include any external sources of contamination, such as pests or physical risks. In accordance with prevailing legislation, packaging is also appropriately labeled. The sealed product is labeled by the operator based on its intended use. So as to ensure the protection of food and feed, it is necessary for the packaging material, namely food contact materials, to be sourced from a certified supplier. This precautionary measure is taken to minimize the potential risks associated with chemical, physical, and microbiological hazards that may pose a threat to the safety of food or feed (Lähteenmäki-Uutela *et al.*, 2021).

13 Future prospects for edible Coleoptera

The Food and Agriculture Organization of United Nation has forecasted that by 2050, there will be over 9 billion people on the planet, necessitating a 100% increase in food production (Belluco *et al.*, 2015; Fels-Klerx *et al.*, 2018). The need for food is driven by the growing human population, but there is a corresponding decline in the amount of land that can be used to grow that food, which is anticipated to be made worse by global warming. Food insecurity would likely worsen as a result of climate change's reduced agricultural land availability (Hasegawa *et al.*, 2018), with low-income nations expected to experience the harshest effects, including an increase in malnutrition and poverty. The gap in food security between countries with higher and lower incomes would widen as a result of this. Therefore, there would be a need for better socioeconomic conditions and food access globally (Chen *et al.*, 2023; Misselhorn *et al.*, 2012). Since edible insects can offer the protein, vitamins, and minerals essential for human health and welfare (Devi *et al.*, 2022; Nowakowski *et al.*, 2022), they have been proposed to be a valuable source of food in areas where people experience malnutrition and food insecurity (Abril *et al.*, 2022). To address the issue of food insecurity, insect producing sectors may be established (Devi *et al.*, 2022; Kipkoech *et al.*, 2023; Lange and Nakamura, 2023).

13.1 *Potential as a sustainable protein source*

The nutritional composition of edible insects exhibits considerable variability, mostly due to the extensive diversity of species involved. Variations in nutritional composition can be observed among edible insect species, even within the same group. These differences can be attributed to factors such as the metamorphic stage of the insect, particularly for species that undergo complete metamorphosis (known as holometabolous species), including ants, bees, and beetles. Additionally, the habitat and food of these insects also contribute to the variability in their nutritional contents. According to van Huis *et al.* (2013), similar to other food items, the nutritional makeup of a food can be influenced by various preparation and processing techniques such as drying, boiling, or frying (van Huis *et al.*, 2013). Protein is recognized as a fundamental dietary requirement. Proteins are mostly derived from animal-based sources, such as meat and fish, as well as plant-based sources, with a special emphasis on legumes. Nevertheless, there is an ongoing debate surrounding the production of meat, particularly ruminant meat, due to several concerns related to the environment, food safety, and animal welfare. To ensure the sustainability of protein production, a recommended dietary modification would involve the utilization of alternate protein sources, such as insects. Insects generally exhibit a high protein content and have superior production efficiency when compared to other common sources of protein (Tuhumury, 2021a). Various species of edible beetles exist, such as aquatic beetles, wood-boring larvae, and dung beetles in both their larval and adult stages (Ramos-Elorduy, 2009). Another observation by XiaoMing *et al.* (2010), Coleoptera, both in the larval and adult stages, has a protein content ranging from 23 to 66 percent. Whereas other researchers reported that Coleoptera in adults stage contains 42.2% of protein and in immature stage it contains 37.3% of protein (Rothman *et al.*, 2014). Edible insects exhibit favorable amino acid compositions that make them viable substitutes for grain proteins. Certain edible bug species have a notable abundance of amino acids, including lysine, tryptophan, and threonine. Cereal proteins, which serve as key staple foods globally, frequently exhibit deficiencies in certain amino acids. The study conducted by Oleen Machona *et al.* (2022) suggests that Tenebrio Molitor mealworms exhibit promising potential as a viable food source for both animals and humans. The research findings indicate that these mealworms possess a favorable nutritional profile, equivalent to that of protein sources like soybeans. Apart from that, it was observed that a cohort of chickens that were provided with a specially formulated stockfeed containing *T. molitor* exhibited a marginally higher mean weight compared to another cohort of hens who were fed a standard basal diet consisting of commercially available broiler stockfeed.

13.2 *Market potential and challenges*

The ability of Coleoptera to transform organic materials into protein allows them to be one of the numerous insects that can address the issue of food loss and waste. Compared to raising other conventional livestock, rearing Coleoptera requires less room, less water, and frequently also less energy (Dobermann *et al.*, 2017; Cadinu *et al.*, 2020). Due to their nutrient profile, insects can also help create diets for humans and animals that are more balanced. Insects effectively convert organic waste and manure into nutrient-rich biomass, acting as a substitute source of minerals and other elements. Insect frass, for example, which is a byproduct of their manufacturing, can be utilized as fertilizer (Barragán-Fonseca *et al.*, 2022; Poveda, 2021). This is the reason why coleoptera serve as a crucial component in the circular economy paradigm, which aims to supplant the traditional notion of "end-of-life" with strategies focused on material reduction, reuse, recycling, and recovery throughout the many stages of production, distribution, and consumption (Moruzzo *et al.*, 2021).

The insect industry has experienced substantial growth in the last decade, garnering increased recognition through widespread media coverage. This attention is often prompted by the introduction of new regulations or the announcement of findings pertaining to its potential in many facets of food chain production. Based on a study conducted by Global Market Insights, the market for edible insects exhibited a valuation above US $112 million in 2019, with a projected growth rate of 47% throughout the period spanning from 2019 to 2026 (Insights, 2018). According to the research conducted by Jongema (2017), Mexico is home to a diverse range of edible insect species, with over 100 varieties available for consumption. Furthermore, the study reveals that there are more than 1,900 edible bug species worldwide. the order Coleoptera, commonly known as beetles, comprises the largest proportion (31%) of commonly consumed insects. Following Coleoptera, the order Lepidoptera, which includes caterpillars, accounts for 18% of consumption. Hymenoptera, consisting of ants, bees, and wasps, ranks third with a consumption rate of 14%. Orthoptera, encompassing grasshoppers, locusts, and crickets, follows closely behind at 13%. Hemiptera, which includes cicadas, planthoppers, scale insects, leafhoppers, and bugs, represents 10% of commonly consumed insects. The orders Isoptera (termites), Odonata (dragonflies), and Diptera (flies) have consumption rates of 3%, 3%, and 2%, respectively (Jongema, 2017). According to a report on the global edible insects' market, beetles held the largest market share in terms of revenue in 2019 (CMI, 2020).

According to a study conducted by Ruby *et al.* (2015), about 4 billion individuals worldwide have expressed their aversion against consuming insects as a source of sustenance (Ruby *et al.*, 2015). Furthermore, it is anticipated that this rejection of insects as a viable food option may persist in numerous regions across the globe (Williams *et al.*, 2016). The promotion of entomophagy faces significant challenges, including legal constraints, safety considerations, and limited consumer acceptance (Rumpold and Schlüter, 2015). The primary obstacles to the acceptability of edible insects among consumers include feelings of disgust, food neophobia, limited awareness, limited availability, and individual personality factors. It is important to acknowledge that insects can serve as etiological causes of disease. Members of the Tenebrionidae family, including *T. molitor* (yellow mealworms) and *Alphitobius diaperinus* (lesser mealworms), have been identified as potential causative agents of canthariasis (Krinsky, 2019; Thrastardottir *et al.*, 2021). The acceptance of edible insects as a food source is contingent upon various factors, including geographical location, dietary preferences, previous exposure, age, gender, and religious beliefs of the individual consumer (Abdullahi *et al.*, 2021).

14 Conclusions

Using edible Coleoptera, or beetles, as a food source for humans is a viable way to address several issues with the global food system. Beetles, which make up around 31% of all edible bug species consumed globally and are consumed by an estimated 2 billion people in Africa, Asia, and America, are important for food security and nutrition. In addition to being nutrient-dense, beetles support plant growth and soil fertility, which maintains ecological equilibrium. Beetle consumption has significant environmental benefits since, in comparison to traditional animal production, insect farming produces lower greenhouse gas emissions, uses less land and water, and offers higher feed convertibility rates. In addition, the insect food market is expanding quickly, bringing cutting edge goods like oils, liquids, and powders that are multipurpose and beneficial for both health and nutrition.

Notwithstanding the advantages in terms of nutrition and the environment, issues including consumer acceptance, safety worries, and legal limitations still exist. In order to fully realize beetles' potential as a sustainable supply of protein, efforts must be made to overcome these obstacles. In order to preserve requirements for food safety and quality, beetle-based product processing and packaging must be done with great care.

Subsequent investigations ought to concentrate on enhancing beetle cultivation and processing methods, investigating novel culinary uses, and tackling consumer attitudes and inclinations. Cooperation between all parties involved – consumers, companies, governments, and educational institutions – is necessary to encourage beetles to be widely accepted as a useful food source.

In conclusion, edible Coleoptera provide a wholesome and sustainable food supply that can support environmental sustainability, increase global food security, and enhance human health. To fully reap the benefits of beetles as a sustainable food source for future generations, further lobbying and research are required.

Supplementary material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.25266340

Author contribution statements

S.A.S.: conceptualization, methodology, validation, formal analysis, resources, writing – original draft, review and editing, visualization, data curation, project administration, investigation, supervision. A.N.Y.: writing – original draft, visualization, data curation. S.S.E.: writing – original draft, data curation, investigation. A.S.A.M.: formal analysis, writing – original draft, visualization. S.A.: writing – original draft. Y.S.W.: resources. B.Y.: review and editing, visualization. S.A.I.: validation, funding.

Conflicts of interest

The authors declare no conflict of interest.

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